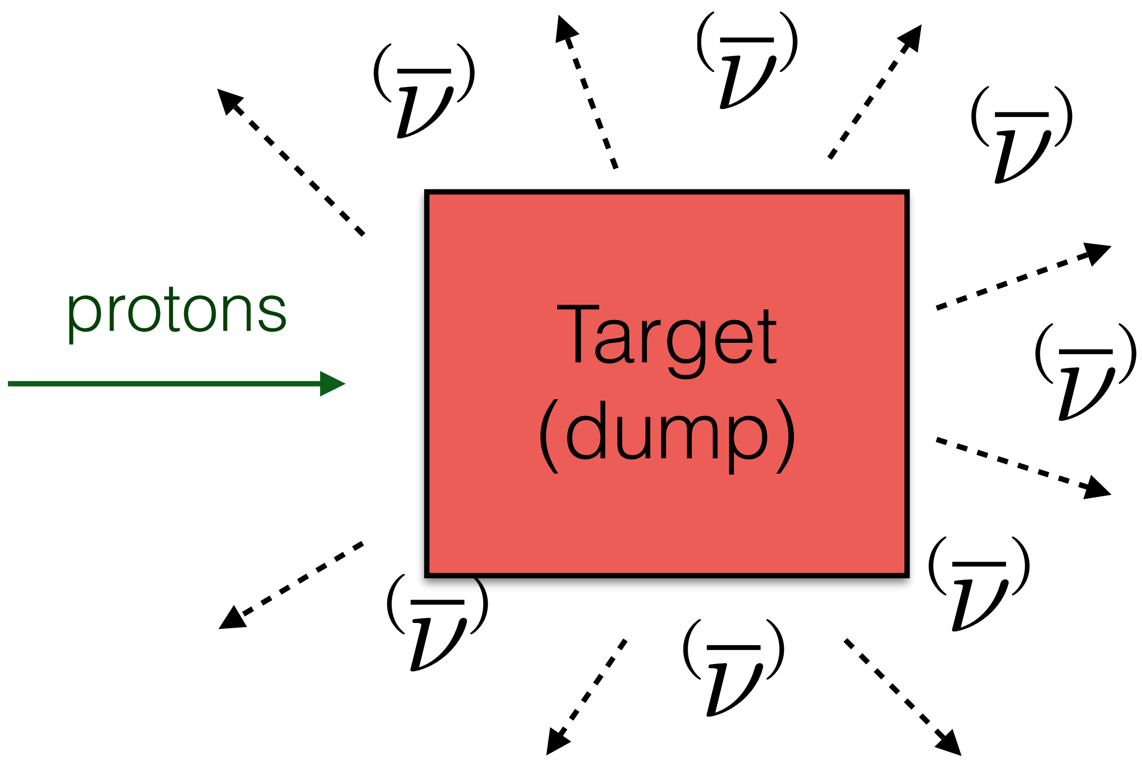
Pion/Muon and Kaon Decay-at-rest Experiments

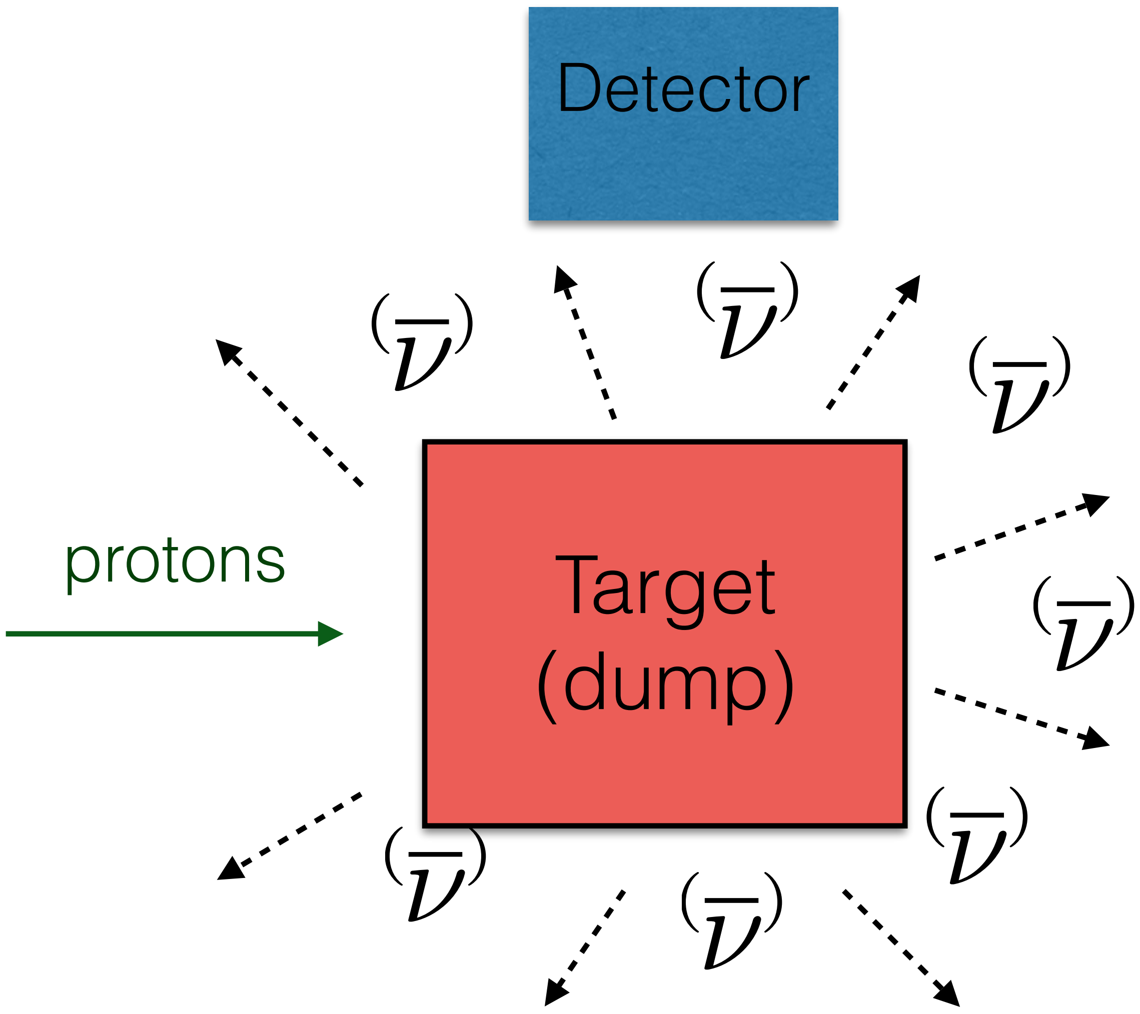


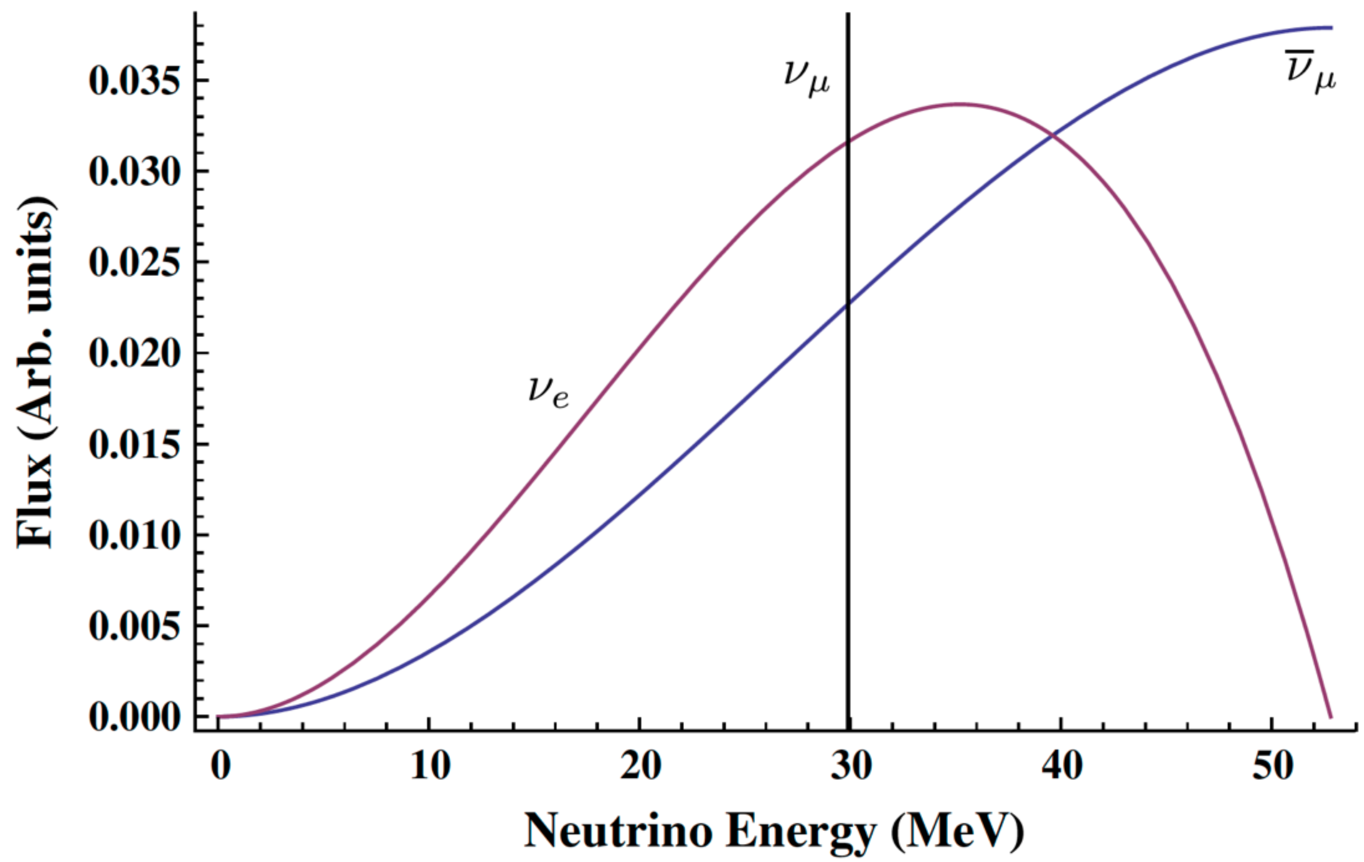
Joshua Spitz, MIT

Workshop on the Intermediate Neutrino Program, 2/5/2015

My focus in this talk is on topics you may not have heard about yet, as well as topics that are not covered elsewhere in this workshop.

Pion and muon decay-at-rest

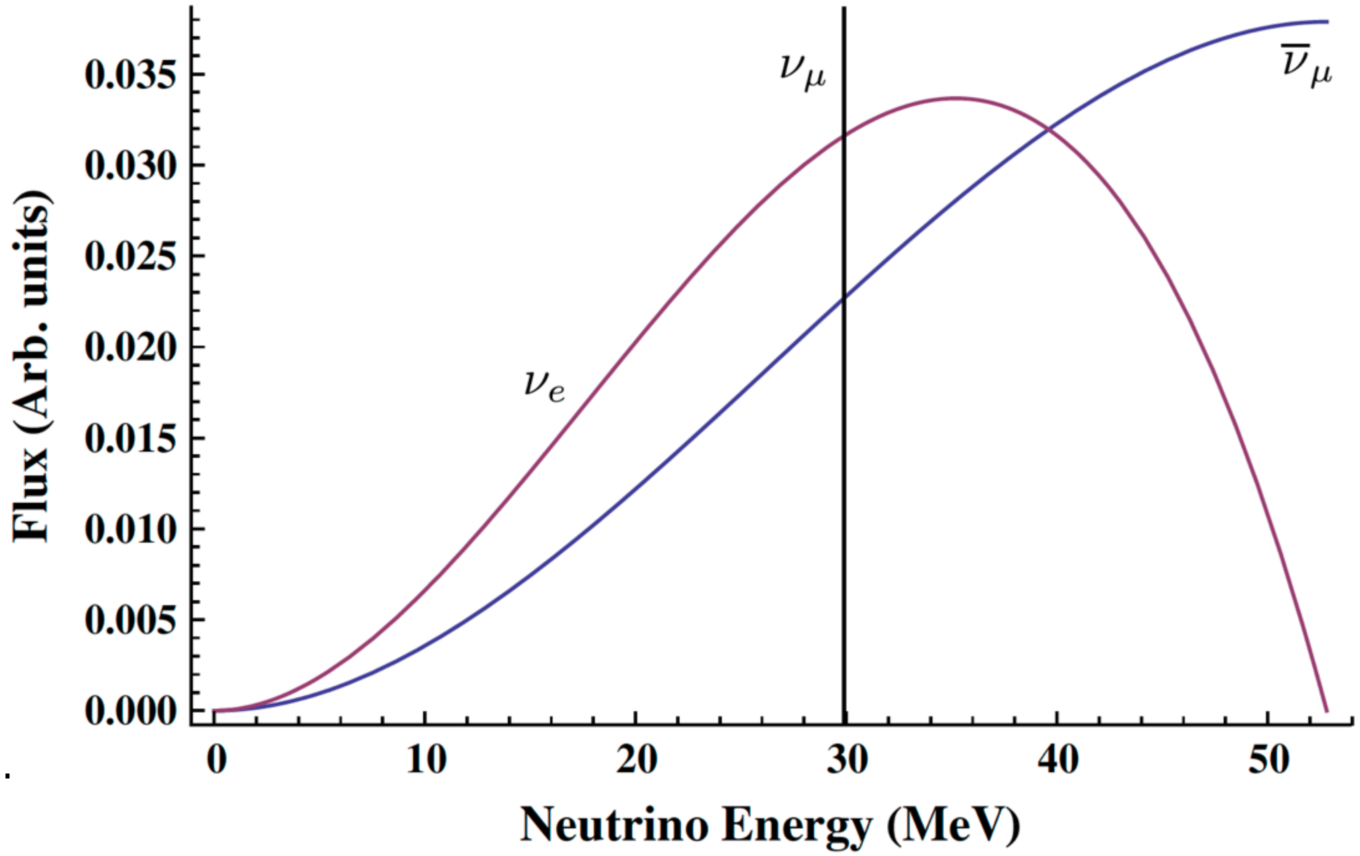




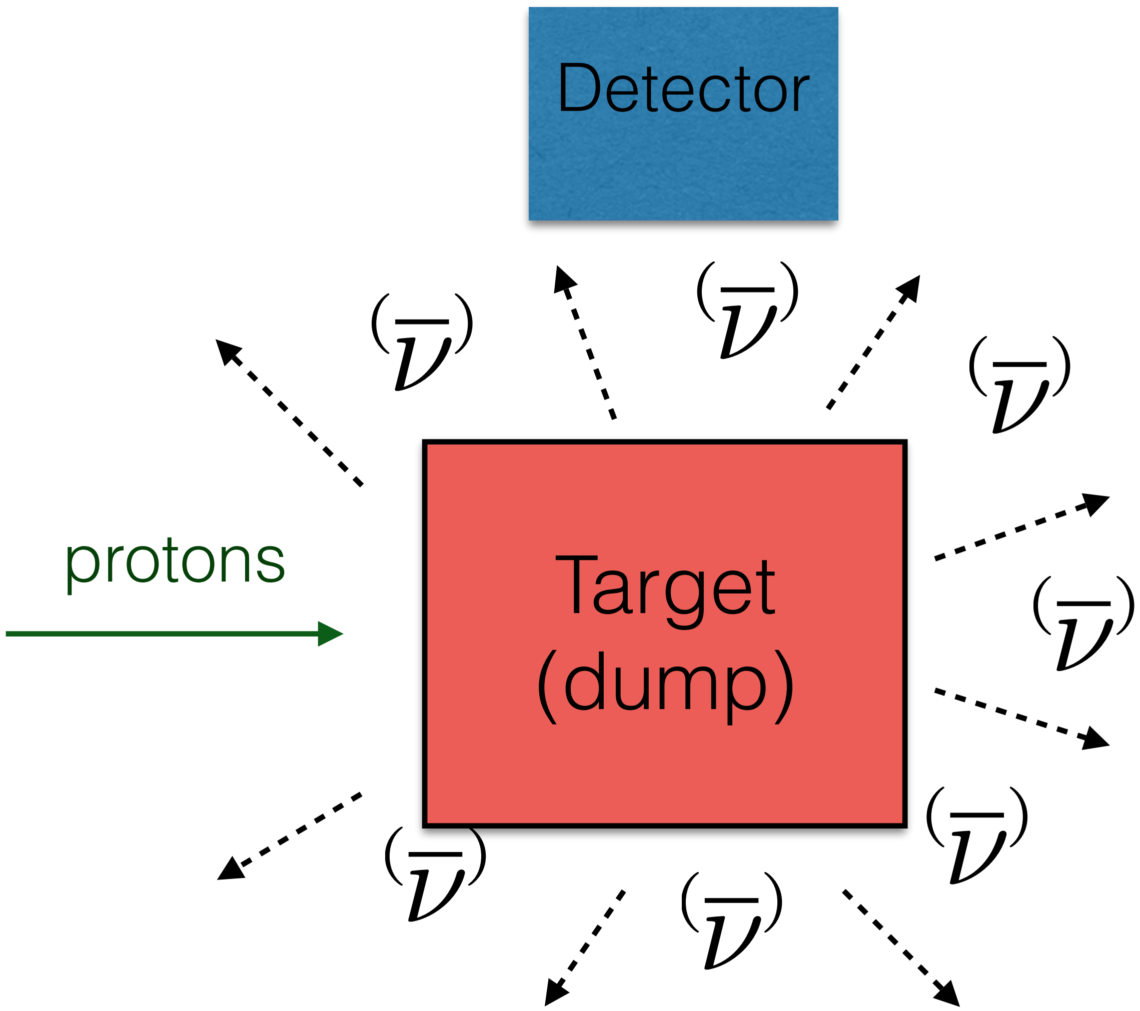
Pion and muon decay-at-rest

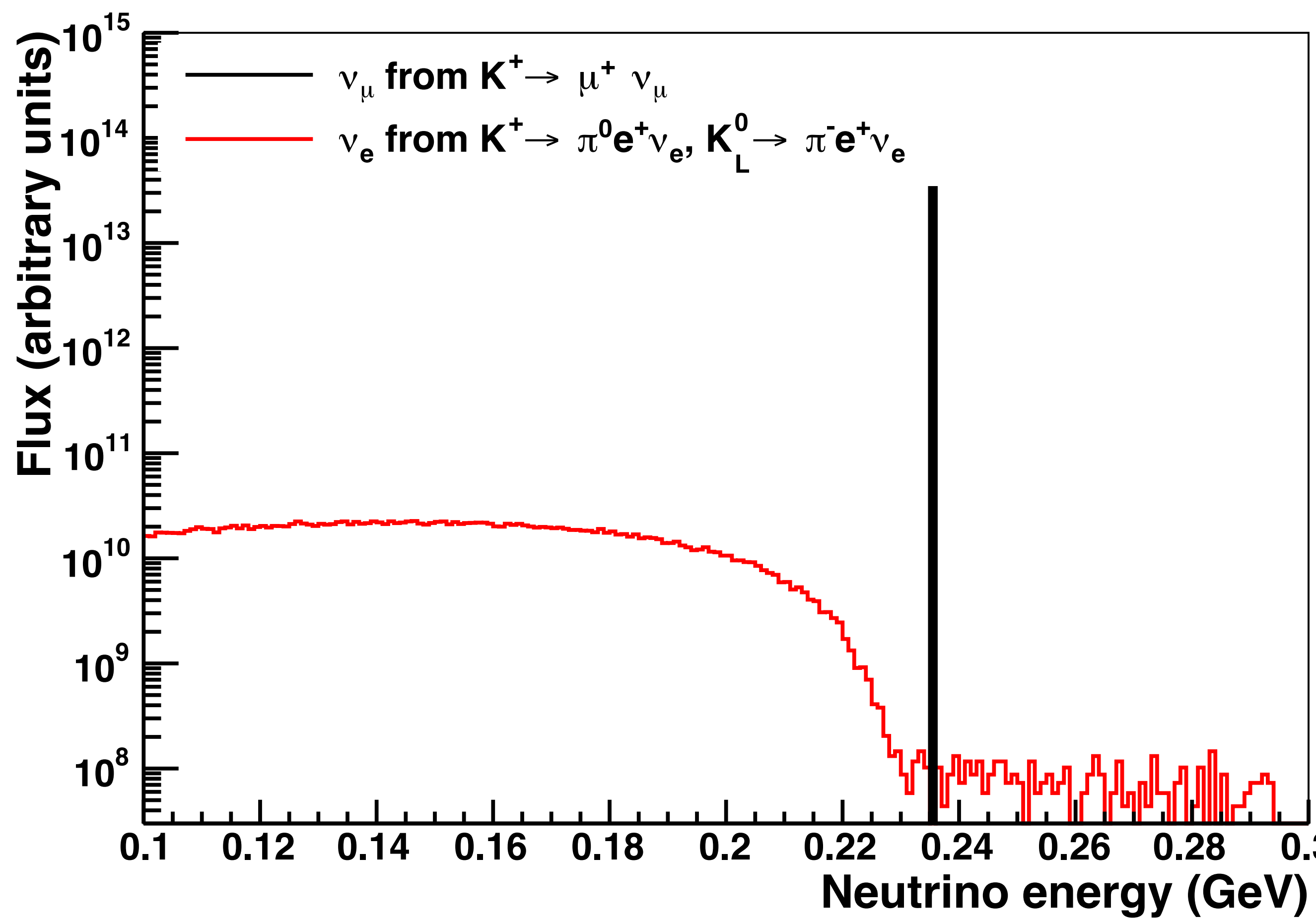
Why are these neutrinos special?

- Known energy shape!
- Energies most relevant for supernovae.
- Coherent scattering xsec is high
- IBD xsec (for nuebar app) is well known.
- IBD events (for nuebar app) are easy to reco/ID.
- Background is low.
- Low energy is nice for (L/E-dependent) osc studies.



Kaon decay-at-rest

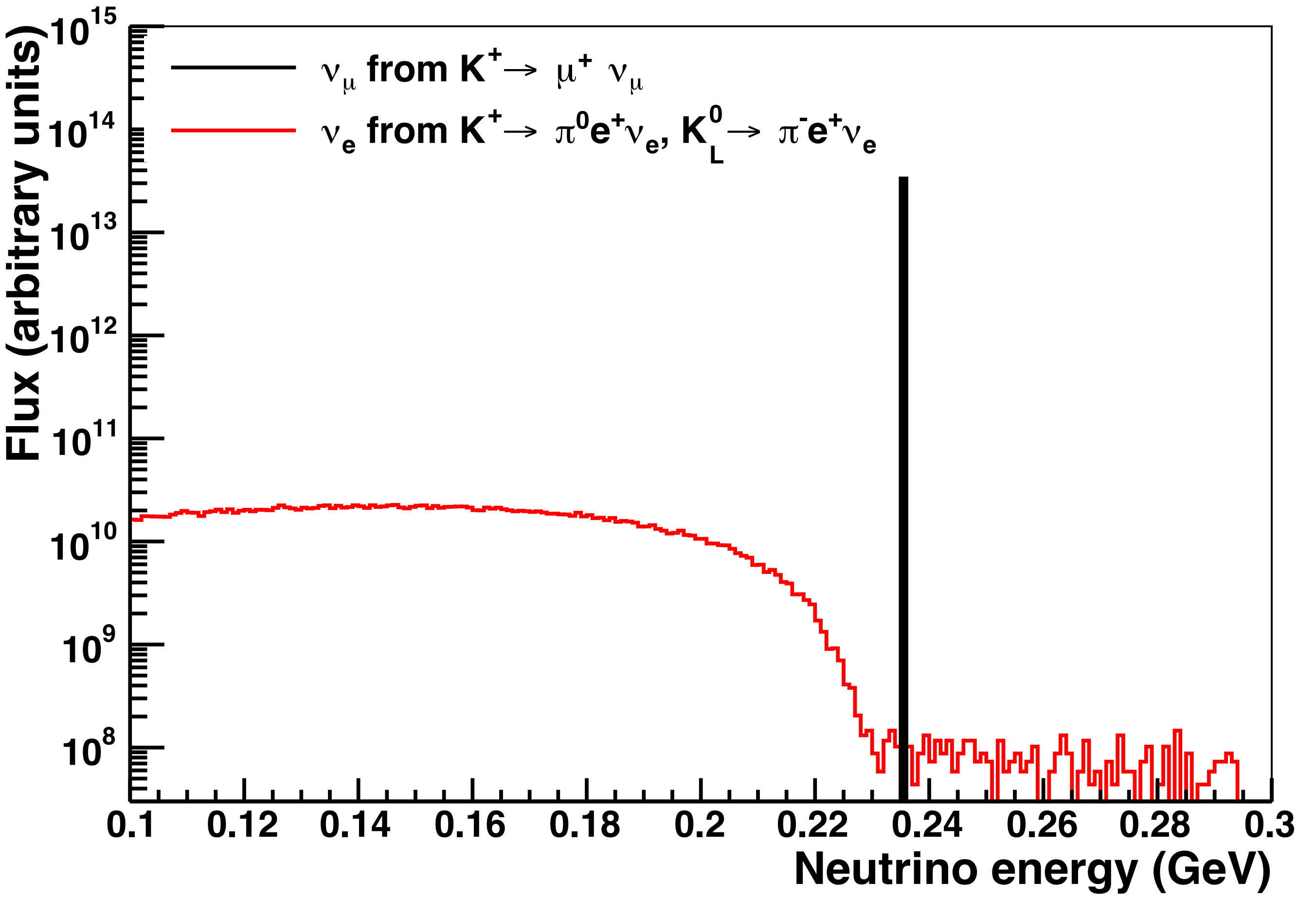




Kaon decay-at-rest

Why are these neutrinos special?

- For once, you know the energy of your muon neutrino. This simple fact is enormously important for a number of potential measurements.
- nue appearance background is low (and measurable).
- Energy is relevant for long baseline exps.



Why are these neutrinos *really* special?

They are (often) free.

Physics opportunities with pion/muon and kaon decay-at-rest

Physics topic	Why is this particularly interesting?
Sterile neutrino	A possible new fundamental particle! Hints from experimental anomalies.
CP violation	Relation to leptogenesis and matter-antimatter asymmetry.
Coherent scattering	Never been measured! Sensitive to NSI.
xsec for supernova	Very poorly measured and highly relevant for SN evolution and future SN detection.
xsec for long baseline	Vital for long baseline CP violation measurements
Weak mixing angle	NuTeV anomaly is still there. Excellent test of Standard Model and NSI.
Dark sector probe	g-2 anomaly is still there. We expect dark sector particle detection eventually.

Where?

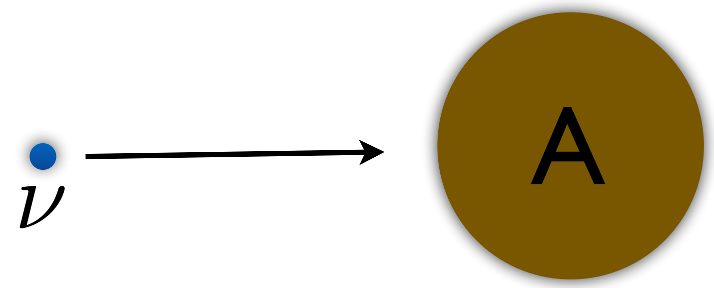
Facility	Location	Proton E (GeV)	Power (MW)	Bunch	Rate
LANSCE	USA (LANL)	0.8	0.8	600 μs	120 Hz
ISIS	UK (RAL)	0.8	0.16	2 $\times$ 200 ns	50 Hz
BNB	USA (FNAL)	8.0	0.032	1.6 μs	5-11 Hz
SNS	USA (ORNL)	1.0	1.4	700 ns	60 Hz
MLF	Japan (JPARC)	3.0	1.0	2 $\times$ 60-100 ns	25 Hz
CSNS	China (planned)	1.6	0.1	$<$500 ns	25 Hz
ESS	Sweden (planned)	2.0	5	2 ms	17 Hz
DAEδALUS	TBD (planned)	0.7	$\approx$1,3,5	100 ms	2 Hz

A few words about a few generic physics opportunities associated with pion/muon decay-at-rest

Coherent neutrino scattering
Supernova xsec
Dark sector searches

Coherent neutrino-nucleus scattering

$$\nu A \rightarrow \nu A$$

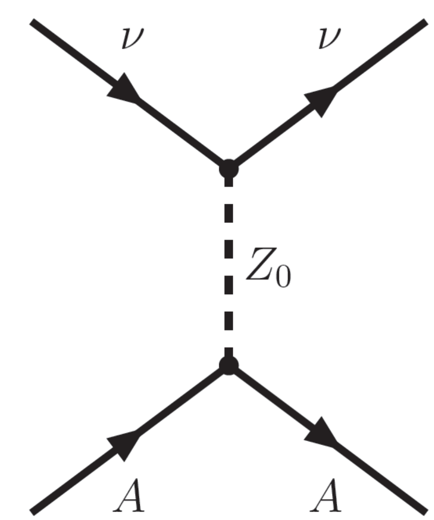


The total scattering amplitude can be approximated by taking the sum of the amplitudes of the neutrino with the individual nucleons when the momentum transfer is small.

$$\frac{d\sigma}{dE} = \frac{G_F^2}{2\pi}\frac{Q_w^2}{4}F^2(2ME)M(2 - \frac{ME}{k^2})$$

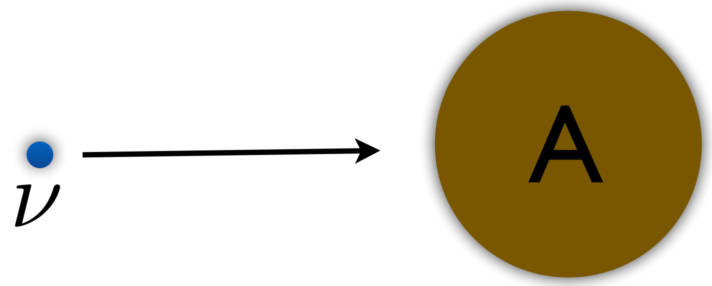
Coherence condition: $E_\nu < \frac{1}{R_N} \simeq 50 \text{ MeV}$ (for typical nuclei)

Coherent ν-A elastic

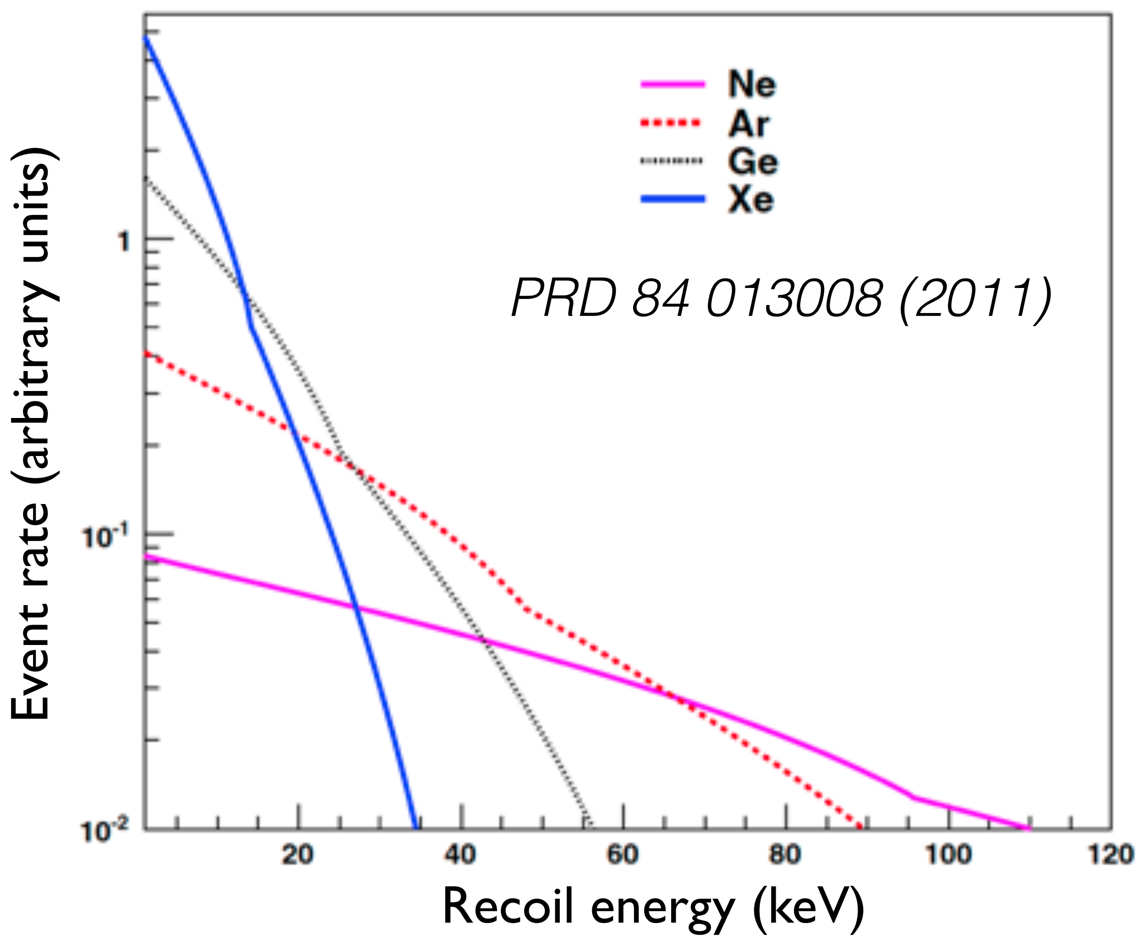


A process well-predicted by the SM with a small theoretical cross section uncertainty (~5%).

An unobserved process with a large cross section ...and a tiny signature



Recoil energies for stopped-pion neutrino source



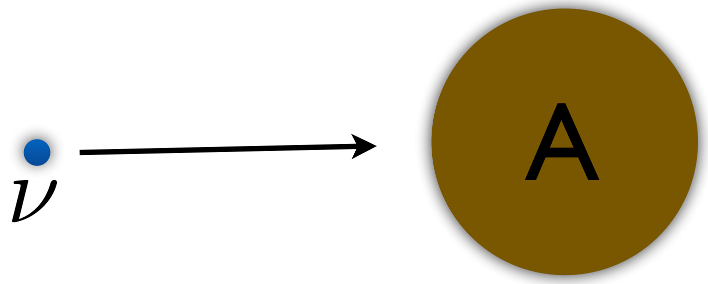
In the few-50 MeV range:

- Coherent ν-A elastic $\sigma \sim 10^{-39}$ cm^2
- ν-A charged current $\sigma \sim 10^{-40}$ cm^2
- ν-p charged current $\sigma \sim 10^{-41}$ cm^2
- ν-e elastic $\sigma \sim 10^{-43}$ cm^2

Very low energy (WIMP-like) recoils

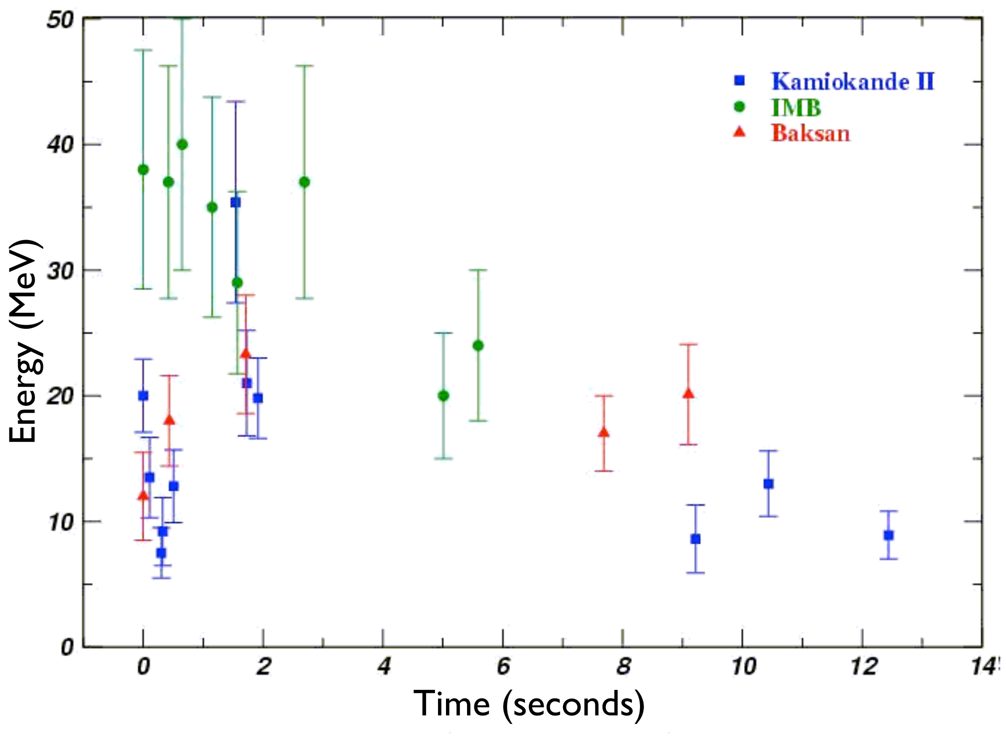
Why is coherent neutrino-nucleus scattering interesting?

- This process has never been detected.
- Differences from Standard Model prediction could be a sign of new physics.
- Supernova process and burst/diffuse neutrino detection.
- Non-standard neutrino interactions.
- Weak mixing angle.
- Neutrino magnetic moment.
- Neutron radius.



Neutrino cross sections for astrophysics

- Cross section measurements at low energy (~0-50 MeV) on various nuclear targets are essential to understanding core collapse supernovae and the neutrino spectra emitted.
  - How were the elements from iron to uranium created?
  - Interpreting supernova burst/diffuse signal on Earth.
- An experiment at an intensity frontier decay-at-rest source can perform measurements of the most relevant neutrino cross sections: ^{2}H, C, Ar, O, Pb, Fe.

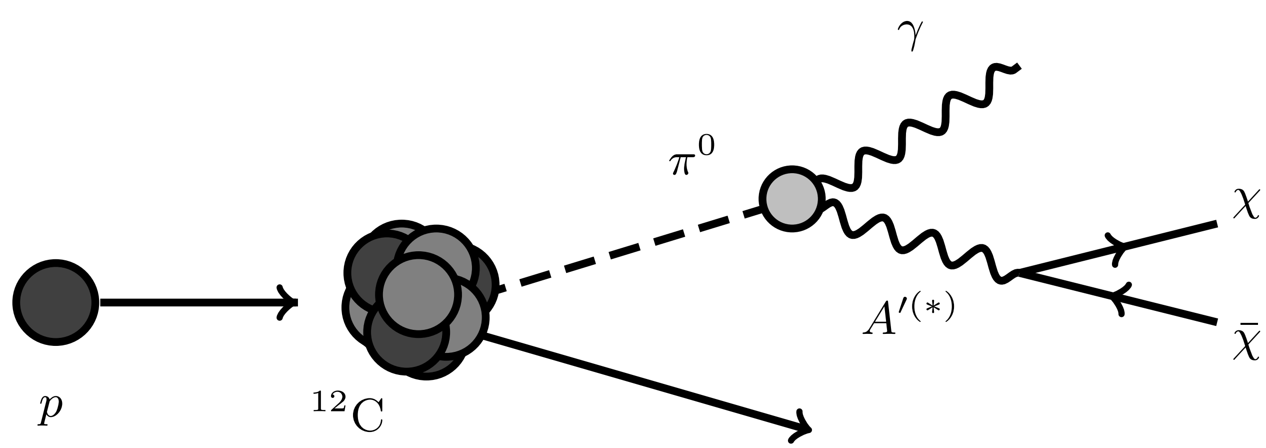


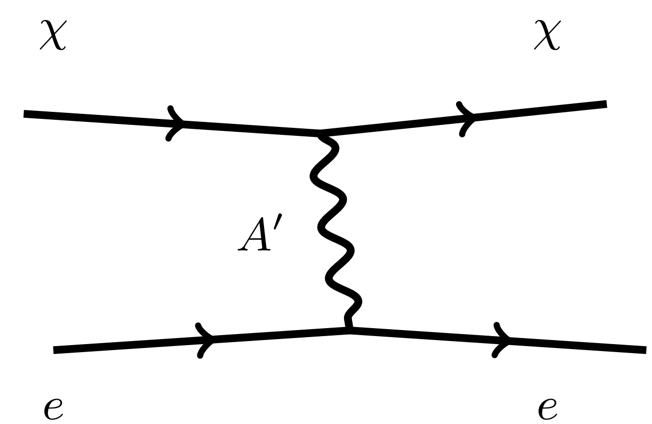
The neutrinos from the next one are already on their way (literally). How do we interpret the spectrum w/o cross section info?

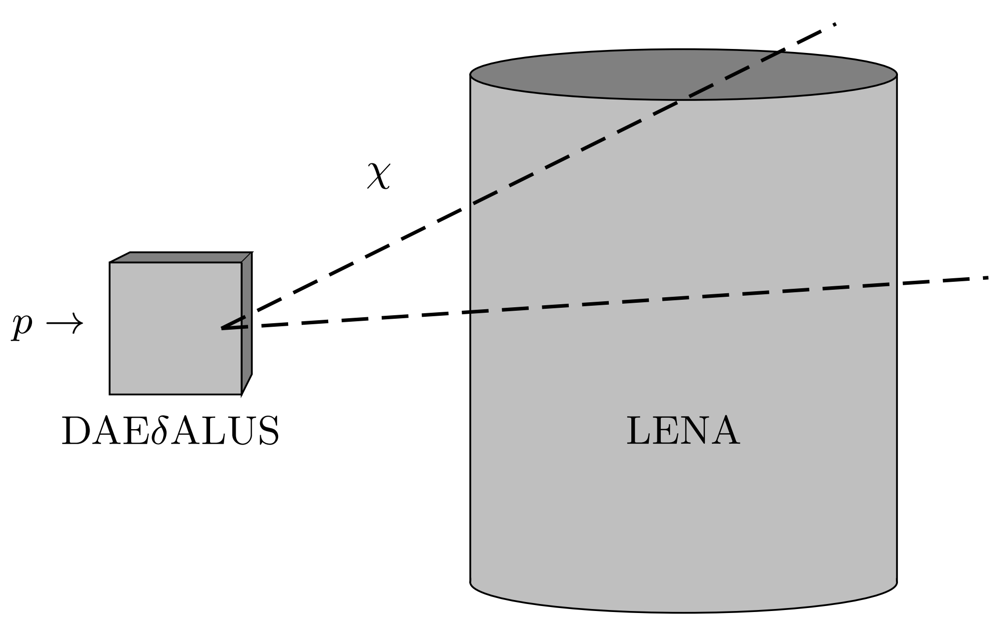
The most relevant cross section on arguably the most important nucleus of all, iron, has only been measured with ~40% precision!

Need more data!

Dark sector searches







- We should remember that these sources, combined with neutrino detectors, can be used to provide sensitive searches for dark sector particles.
- In scenarios with a light weakly-coupled dark sector, a neutral pion can decay to an on-shell mediator (A') to produce pairs of DM particles.
- One can look for elastic-scattering-like interactions in the detector.
- For an excellent new discussion of this prospect for the future (i.e. DAEδALUS at LENA) as well as an examination of past searches (LSND dark sector), see: arXiv:1411.1055.

Experiments

- The DAEδALUS program
- OscSNS
- JPARC-P56
- Decay-at-rest at FNAL (KDAR, CENNS and CAPTAIN)
- COHERENT at SNS

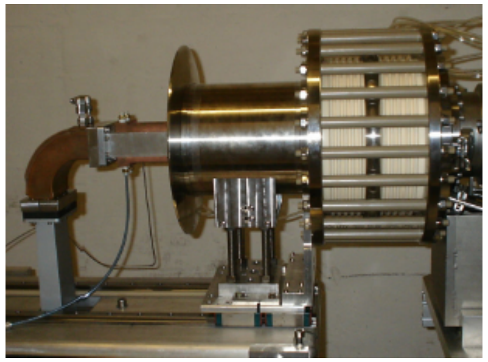
The DAEδALUS program

- The cyclotron as a new, intense source of decay-at-rest neutrinos.
  - High-Q isotope $\boxed{{}^{8}\mathrm{Li} \to {}^{8}\mathrm{Be} + e^{-} + \overline{\nu}_e}$
  - Pion/muon
$$\boxed{\begin{array}{c} \pi^{+} \to \mu^{+}\nu_\mu \\ \mu^{+} \to e^{+}\nu_e\overline{\nu}_\mu \end{array}}$$

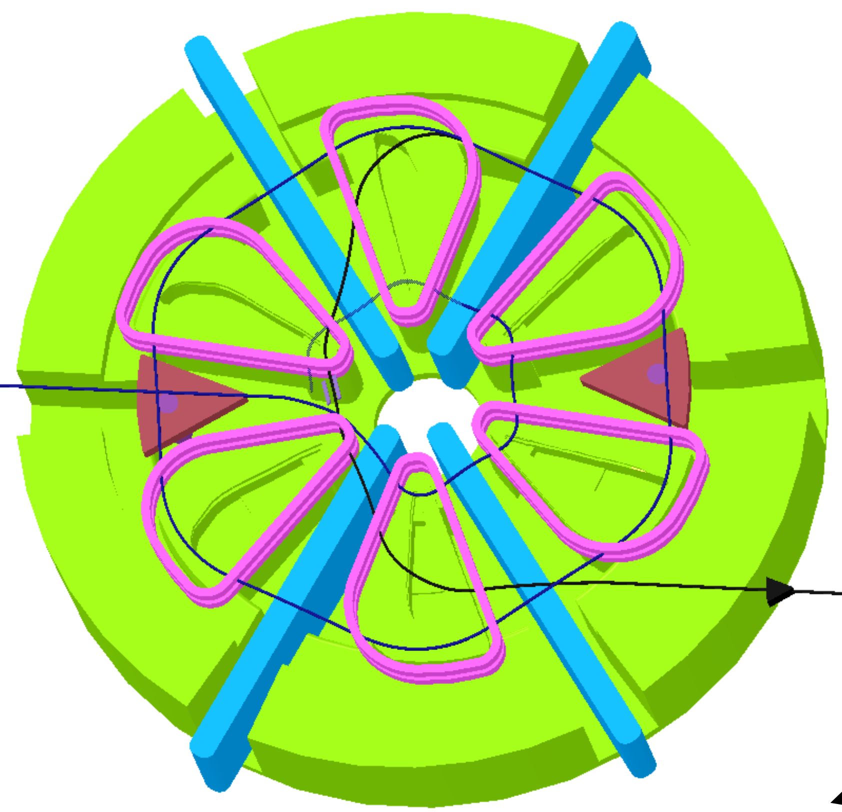
- Combine cyclotron(s) with planned or existing detectors.

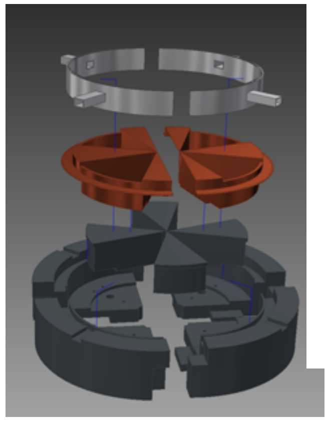
The path to 800 MeV

Ion source

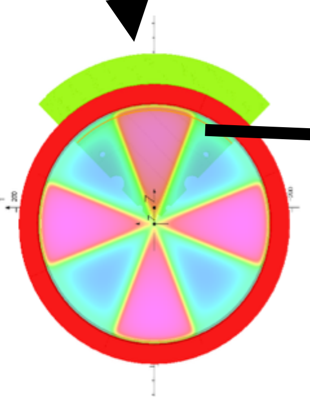


Superconducting ring cyclotron (DAEδALUS)

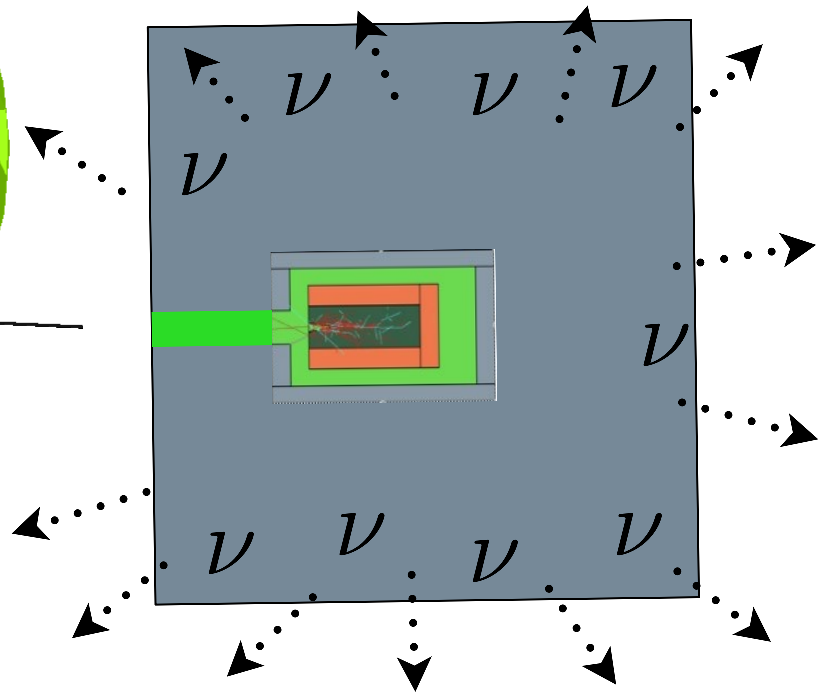




Injector cyclotron (IsoDAR)



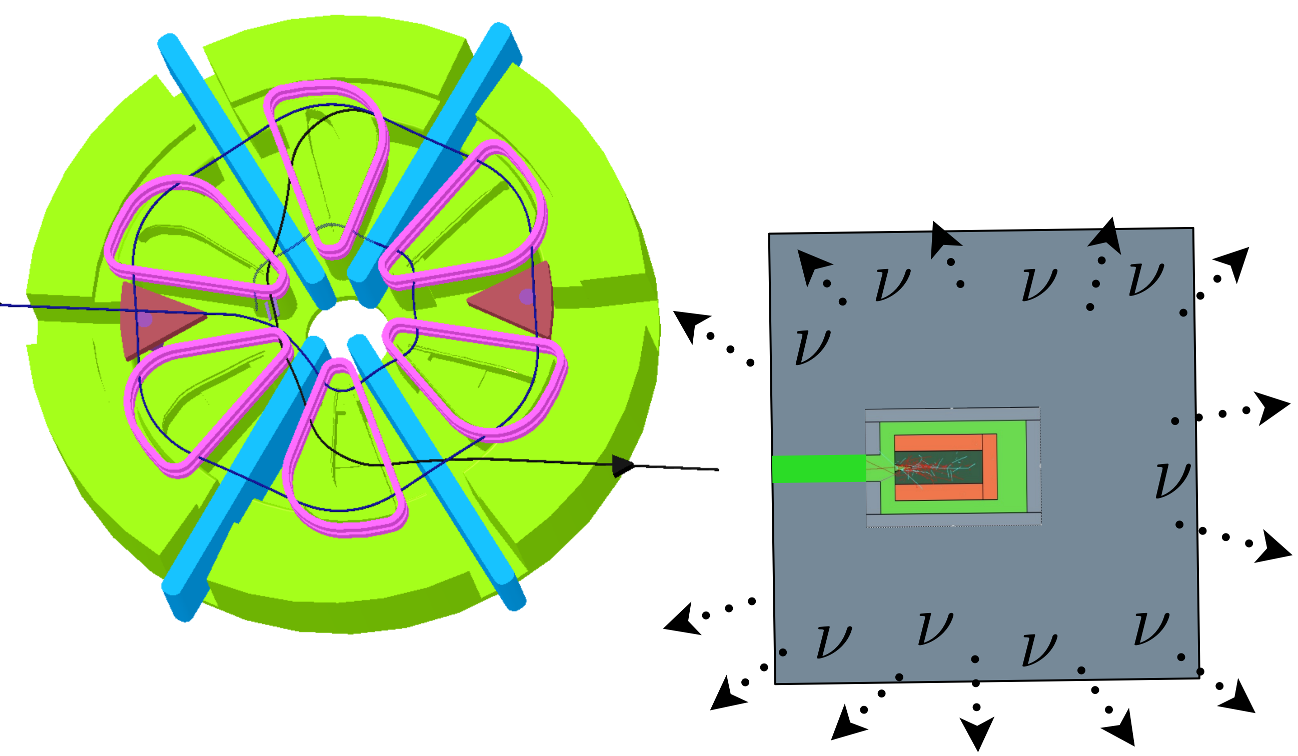
Target/dump

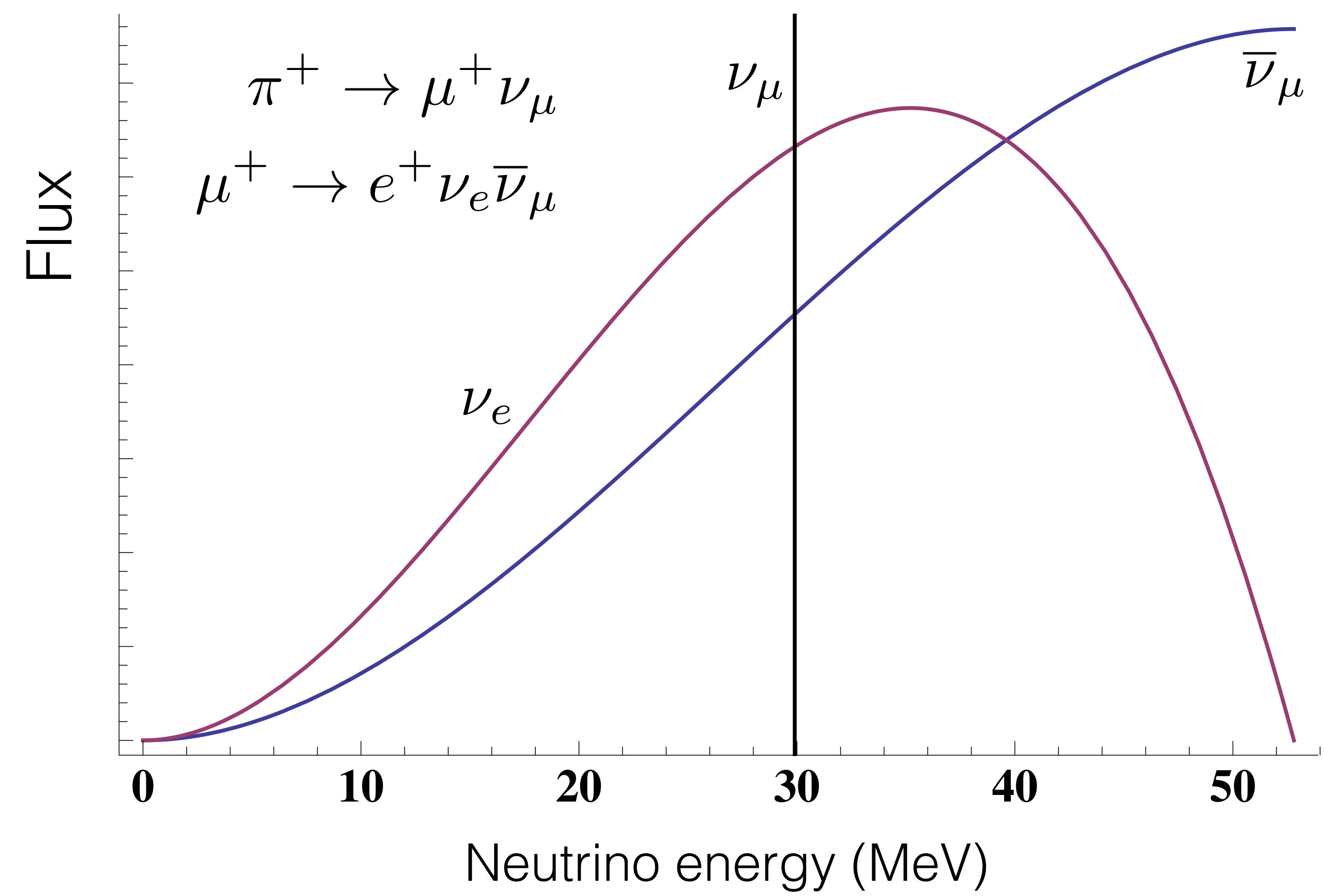


In pursuit of a new paradigm in neutrino physics, DAEδALUS needs near-term engineering R&D money

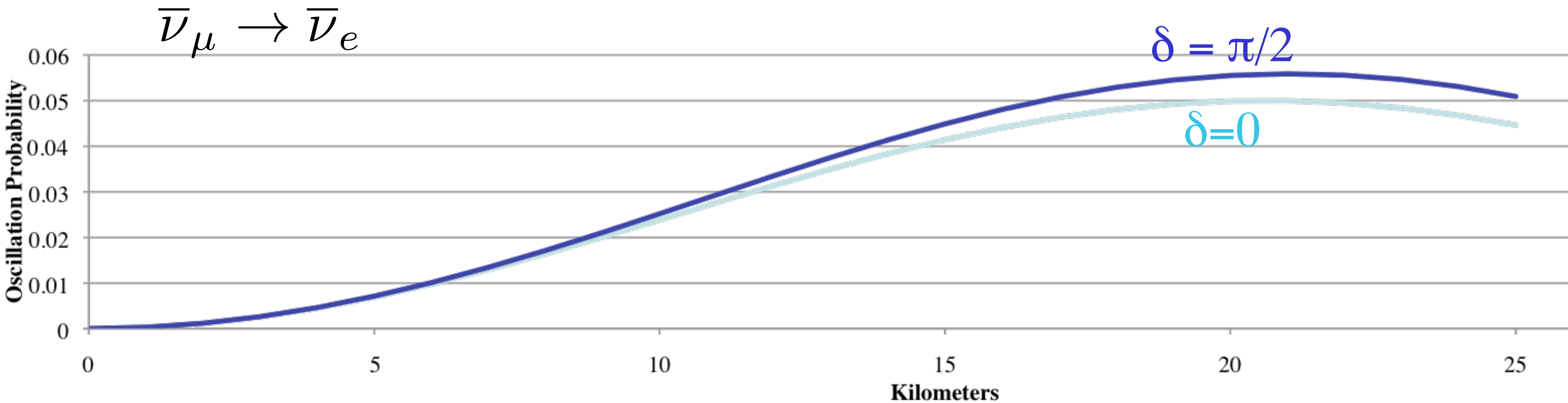
There is a lot we can do if we combine a MW-class decay-at-rest source with a kiloton-scale detector!

DAEδALUS and δ_{CP}





DAEδALUS and δ_{CP}



Near site → Constrains initial flux

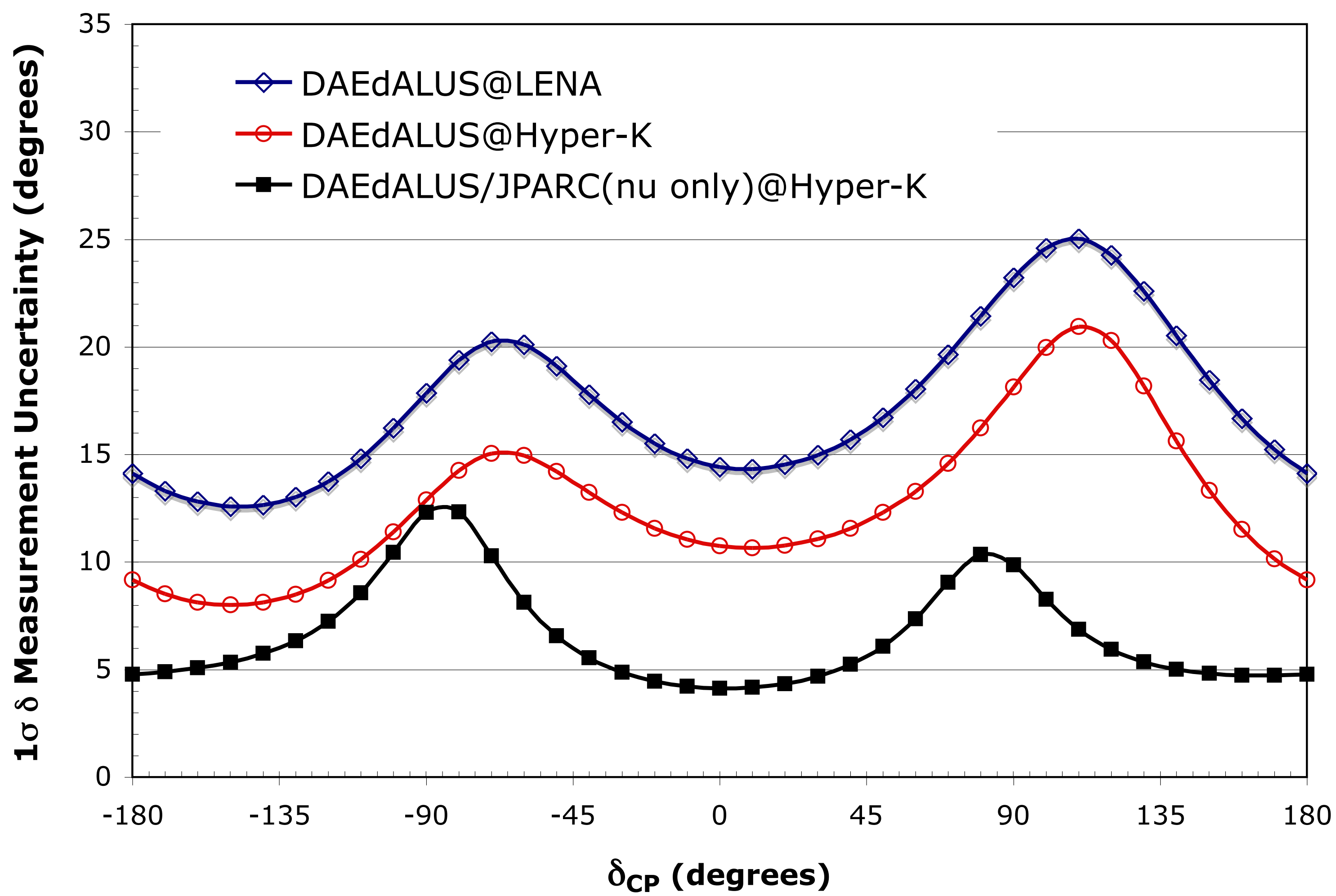
Mid site → Constrains rise probability

Far site → Fit for $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ appearance

Near site gives absolute normalization to 1% via ν_e-e
Relative flux between sites can be constrained with $\nu_e O$ ($\nu_e C$)

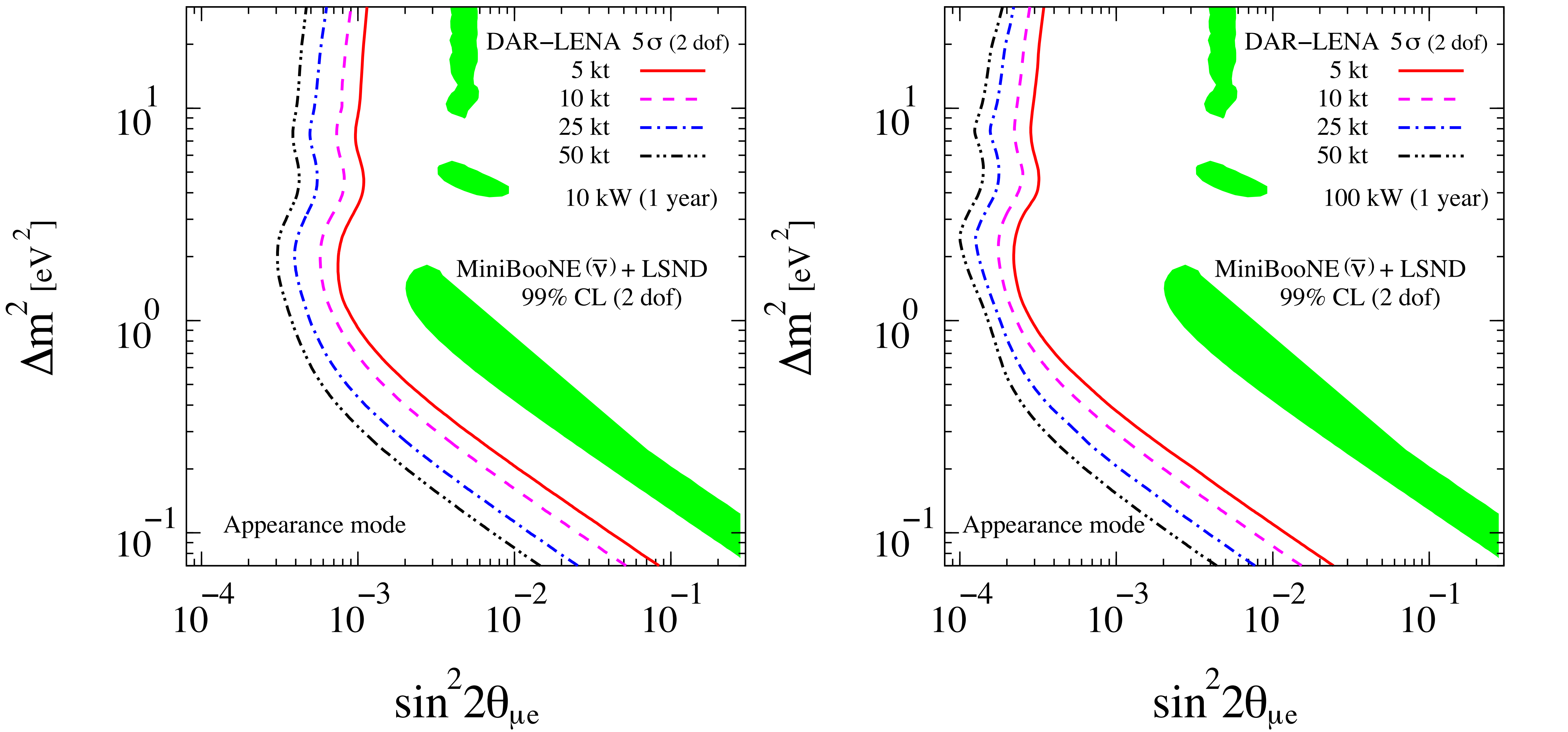
δ_{CP} sensitivity

- DAEδALUS has strong δ_{CP} sensitivity by itself.
- Can be combined with long-baseline data (e.g. Hyper-K) for enhanced sensitivity.
  - Good statistics with anti-neutrinos, no matter effects, orthogonal systematics.
  - Big discoveries want (need?) multiple, independent experiments.



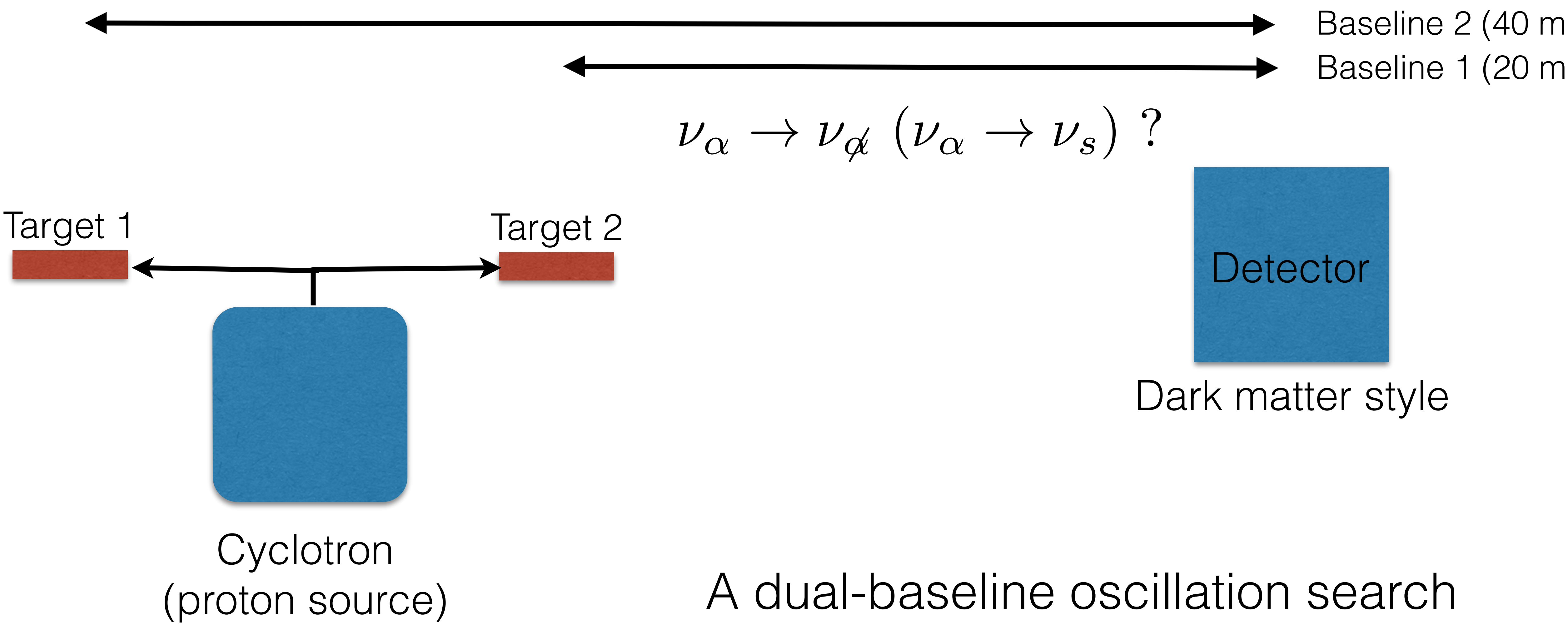
DAEδALUS and sterile neutrinos

JHEP 1112 085 (2011)



Combining DAEδALUS with an ultra-large detector (e.g. LENA) would provide excellent sensitivity to a sterile neutrino.

DAEδALUS and sterile neutrinos (w/ coherent scattering)



A dual-baseline oscillation search

Phys. Rev. D 84 013008 (2011)

Phys. Rev. D 86 013004 (2012)

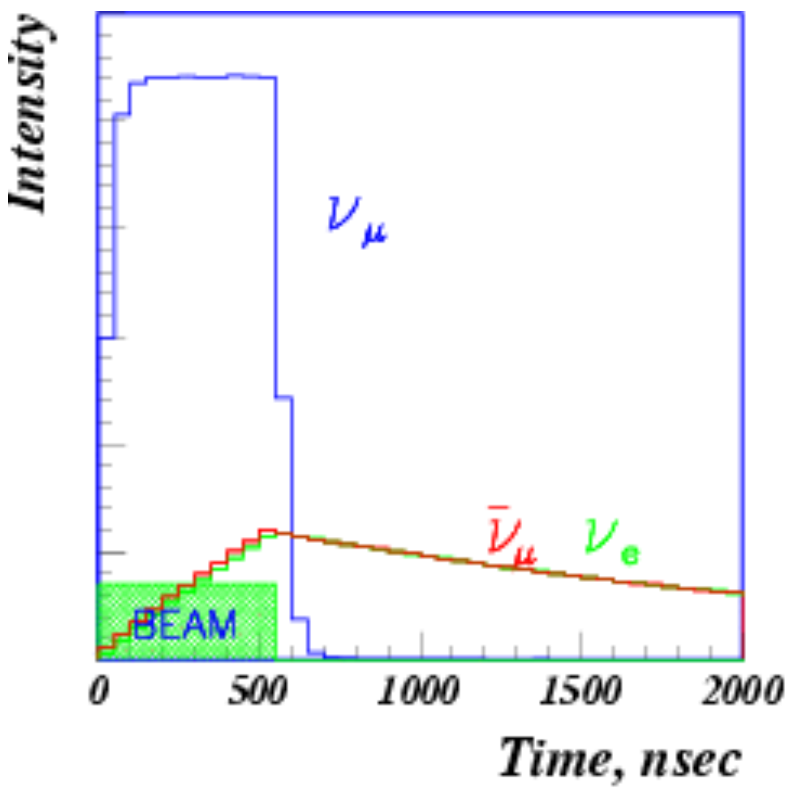
Advantage of the neutral current in a sterile search

- The disappearance of neutrinos interacting via the neutral current is a strict probe of active-to-sterile oscillations.
    - No complicating contributions from active-to-active disappearance.
- Could definitively establish the existence of the sterile neutrino, especially when considered in combination with charged-current-based searches.

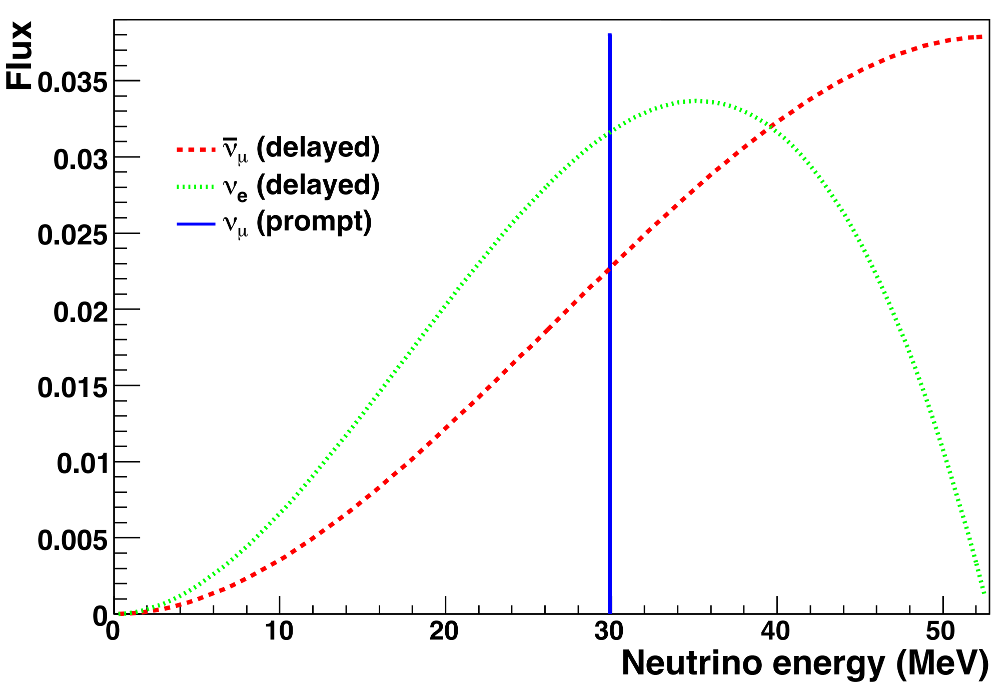
$$\begin{aligned} P(\nu_\alpha \to \nu_{\text{active}}) &= 1 - P(\nu_\alpha \to \nu_s) \\ &= 1 - \sin^2 2\theta_{\alpha s} \sin^2(1.27 \Delta m^2 L/E) \end{aligned}$$

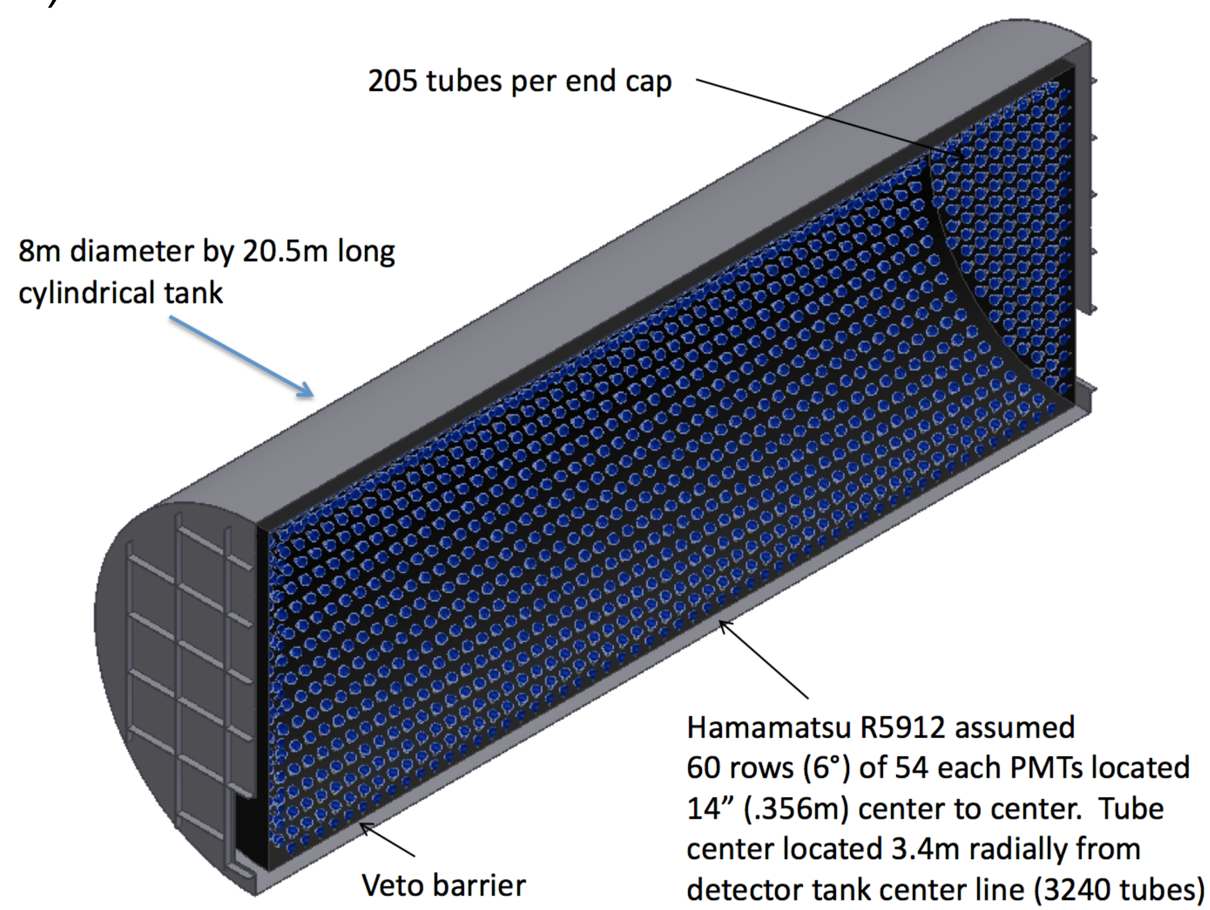
$$\sin^2 2\theta_{\alpha s} = 4|U_{\alpha 4}|^2 |U_{s4}|^2$$

OscSNS



- A proposed LSND-style decay-at-rest experiment at the 1.4 MW SNS (1 GeV protons on an Hg target).
- $20M-scale.
- Can provide *definitive* coverage of the sterile neutrino anomaly region with an 800 ton LS detector, 60 m away.
- Cross section measurements relevant for supernovae as well (^{12}C).

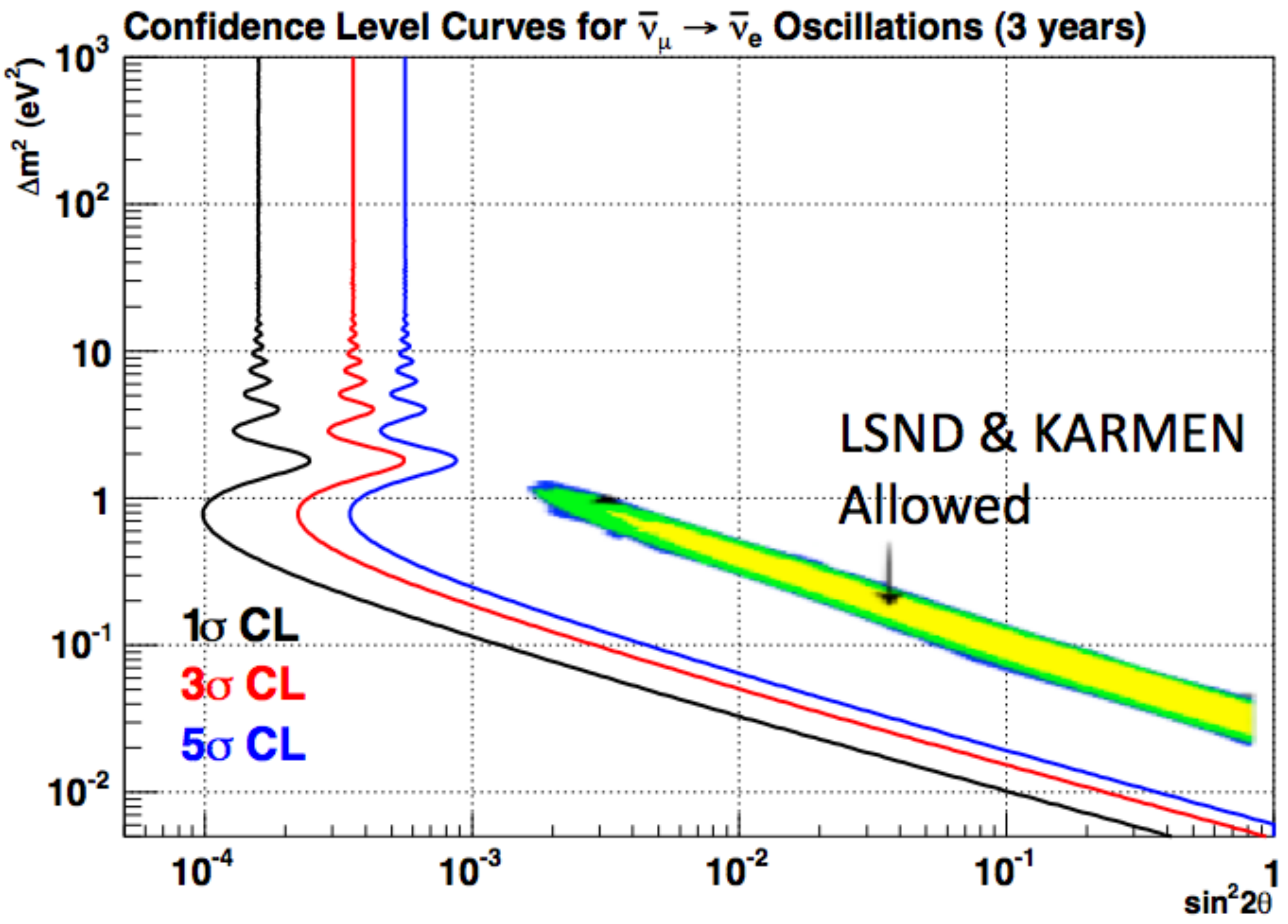




OscSNS seems to solve all of the usual quibbles about LSND

	LSND	OscSNS	Notes
Baseline	30 m	60 m	Reduced in-beam background
Orientation	Detector in front of beam	Detector behind beam	Reduced in-beam background
Beam power	0.8 MW	1.4 MW	
Beam pulse	600 μs,120Hz	695 ns, 60 Hz	Reduced steady-state background
Beam kinetic energy	798 MeV	1000 MeV	
Detector mass	167 ton	800 ton	
Detector technology	Liq. scint. w/ 25% photocoverage	Liq. scint. w/ 25% photocoverage	Better PMT QE expected in OscSNS

OscSNS sensitivity



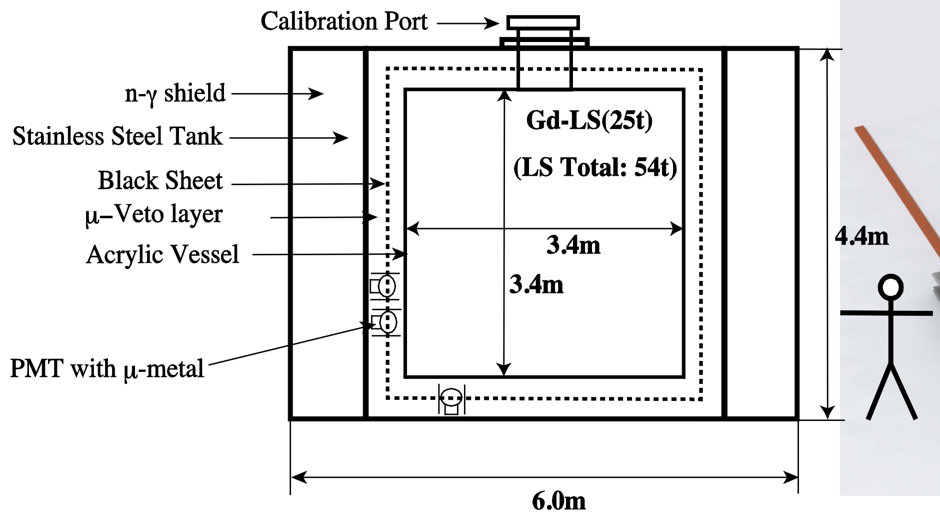
OscSNS White Paper, arXiv:1307.7097

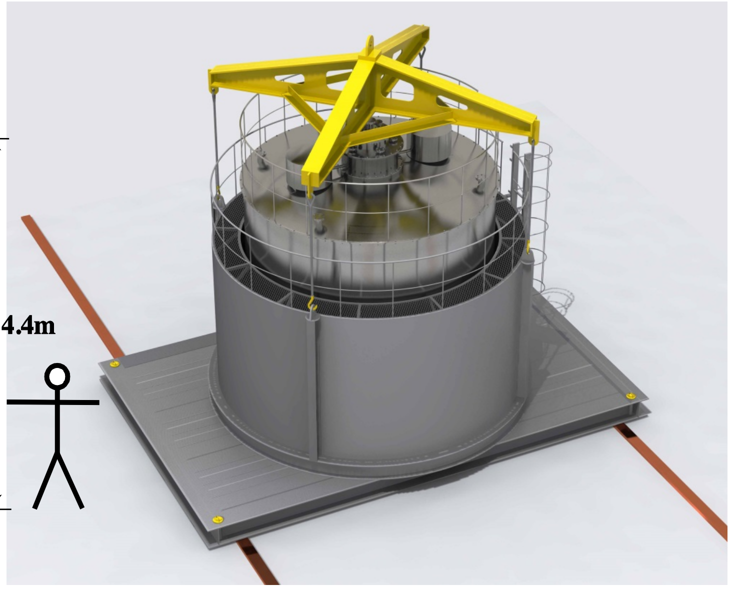
OscSNS, the LSND approach

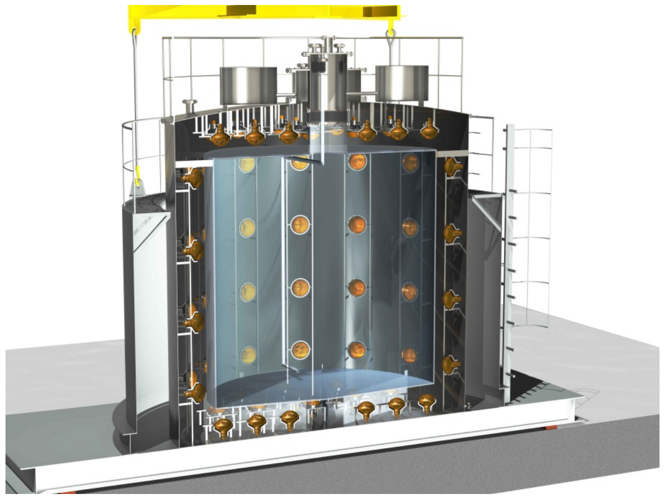
- There is a reason the LSND anomaly still exists almost 15 years later. **It was a pretty sensitive experiment!**
- The Spallation Neutron Source at Oak Ridge, by far the most intense source of non-reactor neutrinos in the world (1.4 MW of protons on target) is in need of neutrino detectors! Remember that the BNB is ~32 kW of protons (in an admittedly apples-to-oranges comparison)!
- If you can rule out LSND with an LSND-style experiment, you have definitively resolved the sterile neutrino issue.
- If you can rule out LSND with a pion DIF experiment in neutrino mode, there still may be questions. See: differences between neutrinos and anti-neutrinos.

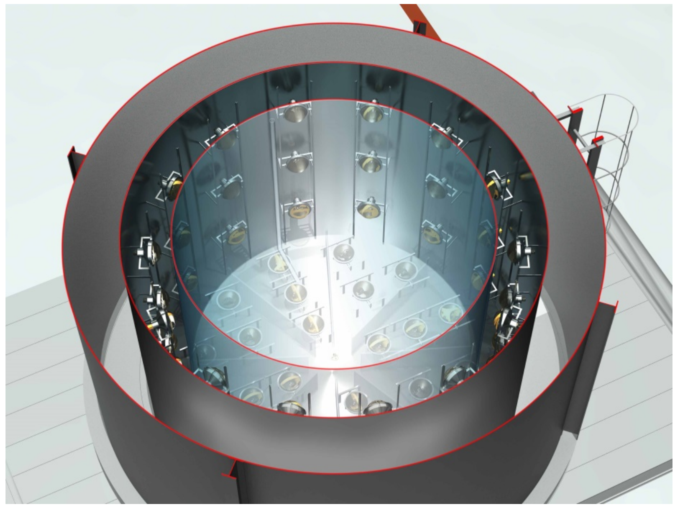
JPARC-P56

- The JPARC-P56 experiment (proposed Stage 1 approval, $5M scale) is very similar to OscSNS.
- An eventually 1 MW spallation source, with 3 GeV protons on a Hg target.
- Phased approach with “Phase 1” proposal to put 2x25ton Gd-LS detectors ~20 m (TBD) away from the source to do an LSND-style experiment.





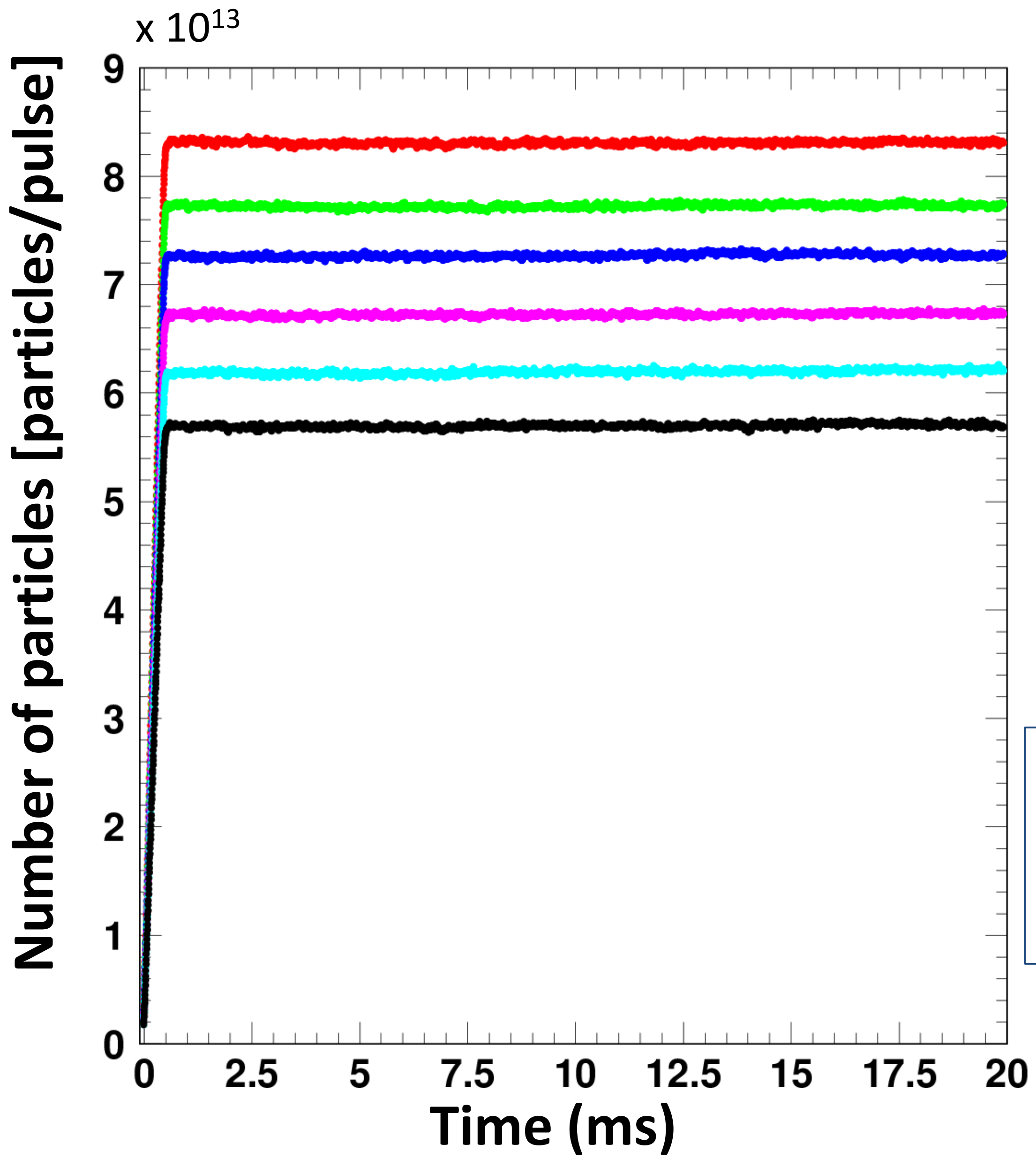




1 MW demonstrated at JPARC-MLF!

Result of the RCS 1-MW trial

2014/12/27



8.32×10^{13} : 999 kW-eq
7.71×10^{13} : 926 kW-eq
7.24×10^{13} : 869 kW-eq
6.70×10^{13} : 804 kW-eq
6.17×10^{13} : 741 kW-eq
5.66×10^{13} : 679 kW-eq

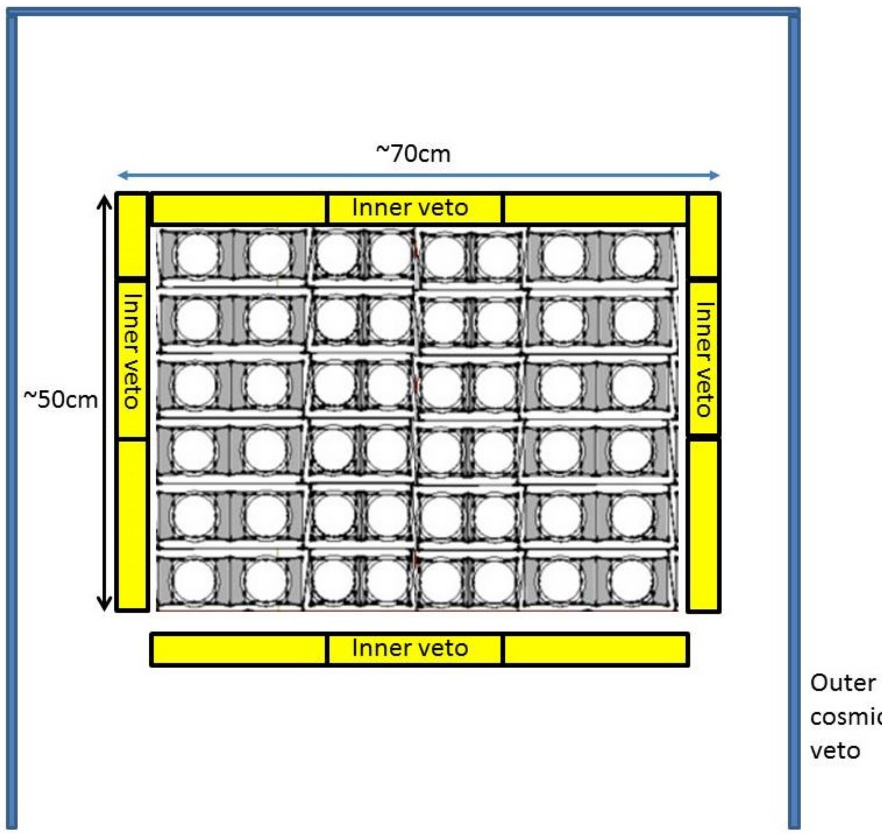
2014年12月27日午前7時31分
1バンチ当たりの粒子数:8.32×10^{13}
（～1MW)
ビーム加速成功！

Please note:
this was a short test!

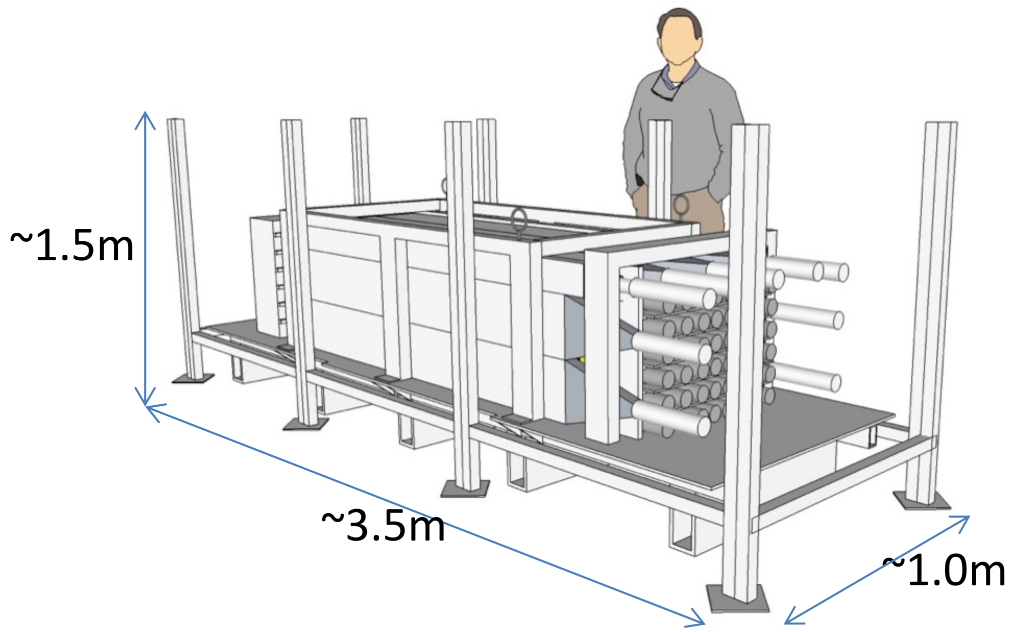
RCS/MLF is now slowly increasing the beam power from 300 kW (current) to maybe ~500 kW in this JFY.

-From T. Maruyama

Is background at MLF ok?



- Direct measurements have been made w/ 500 kg of plastic scintillator and smaller ~10 kg detectors with various levels of shielding and at various positions relative to the source.
  - Beam fast neutrons (n+p (or C) -> X+π; π-> μ -> e)
  - Accidentals
    - Prompt; gammas or neutrons from cosmics.
    - Delayed; gammas or neutrons from beam.



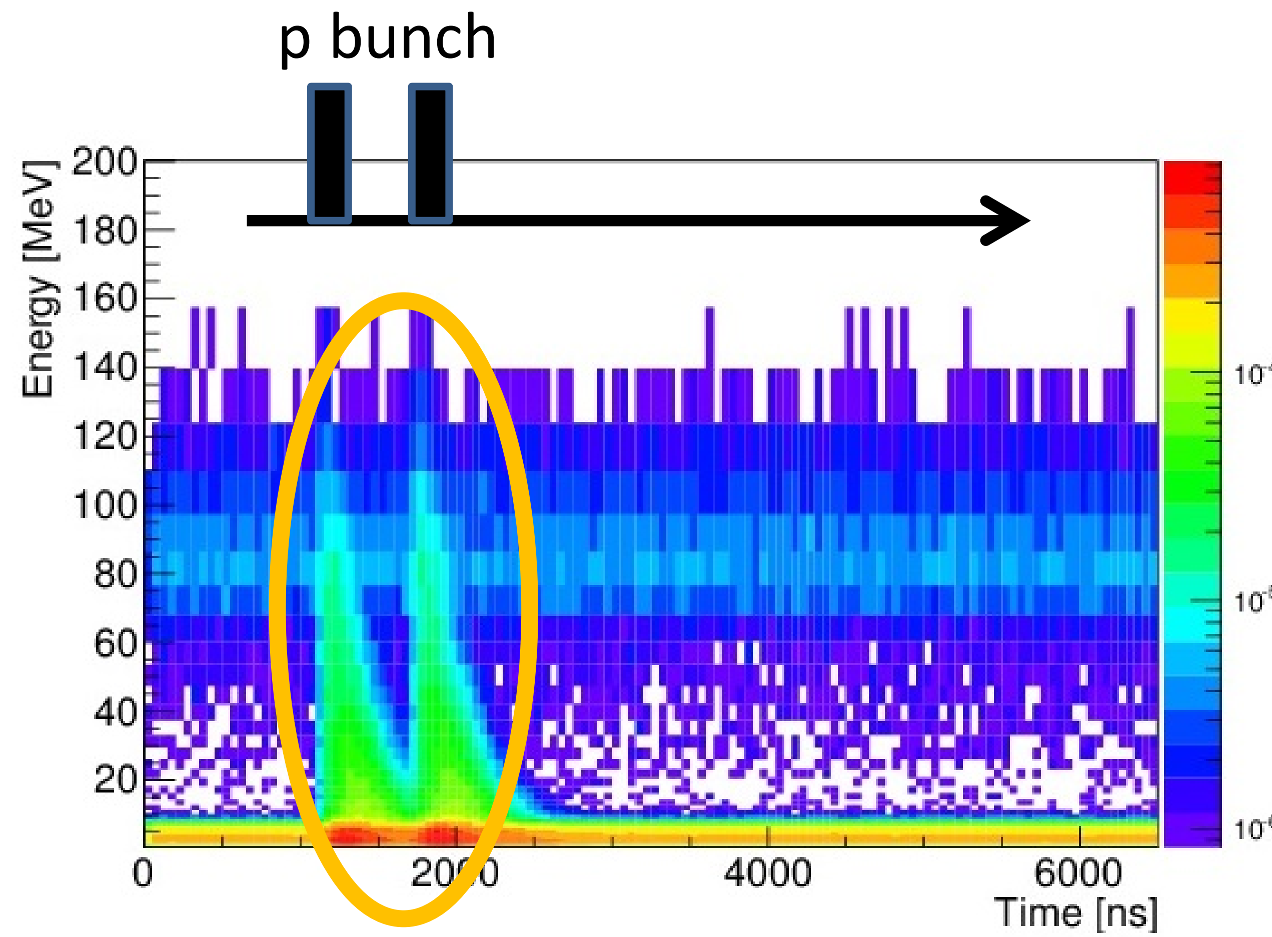
Selection criteria for IBD

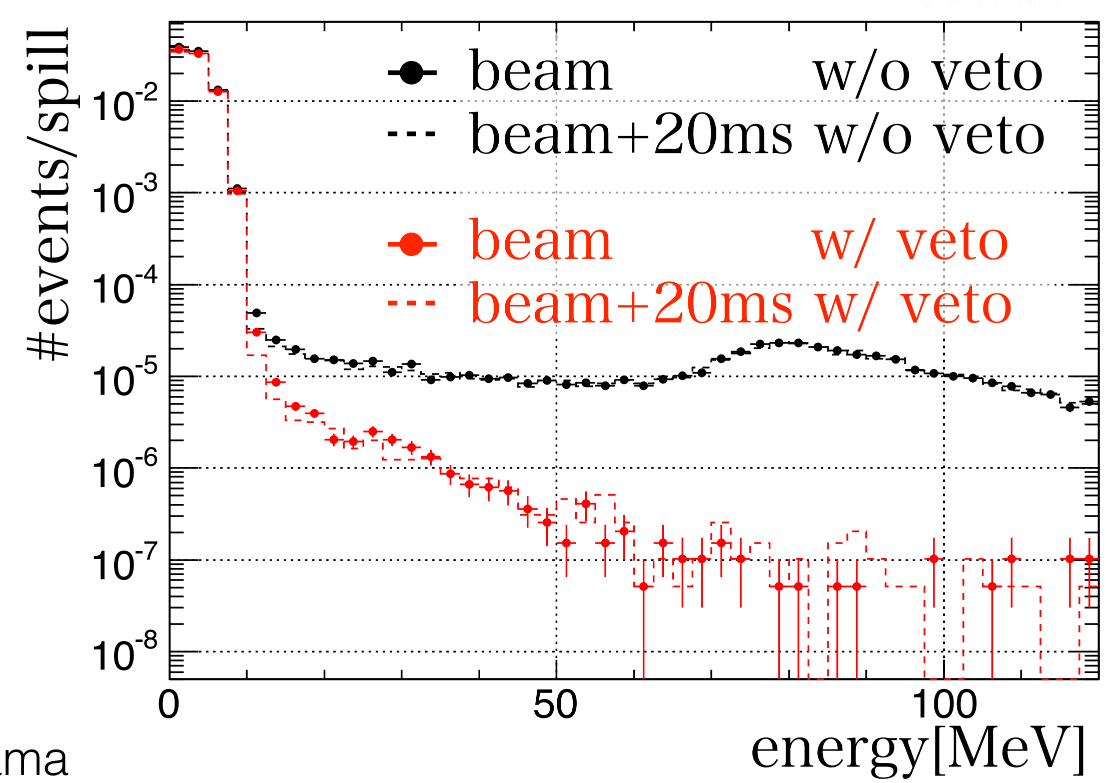
	Time from beam	Energy
Prompt signal	1<T<10μs	20<E<60MeV
Delayed signal	T<100μs	6<E<12MeV

From T. Maruyama

Is background at MLF ok?

- Fast neutron background is OK for IBD at 24 m baseline.
- Some additional lead shielding is required for accidental gammas.
- Shielding may be an issue for in-time events (pion and kaon neutrinos). This requires further study.





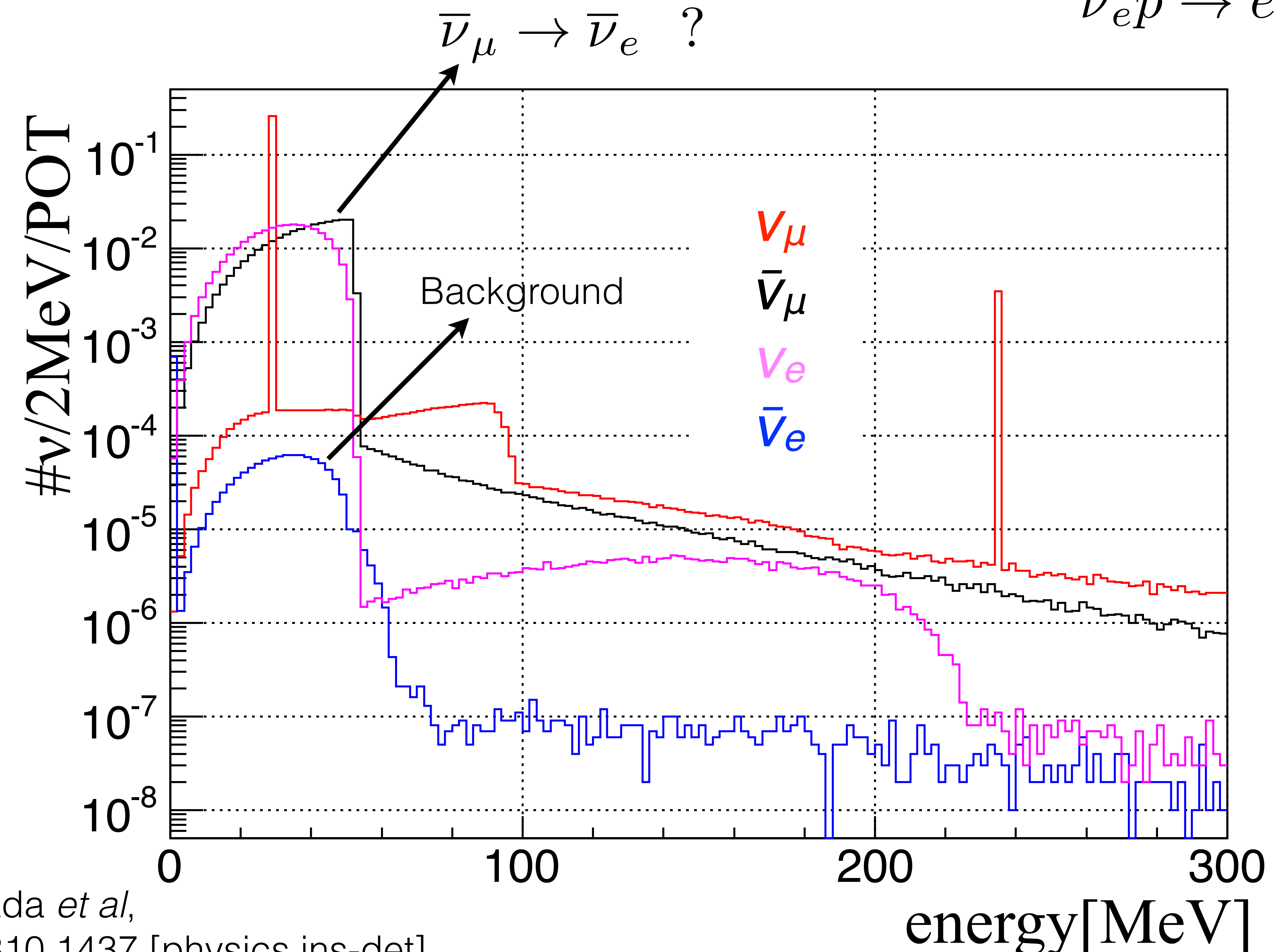
Selection criteria for IBD

	Time from beam	Energy
Prompt signal	1<T<10μs	20<E<60MeV
Delayed signal	T<100μs	6<E<12MeV

From T. Maruyama

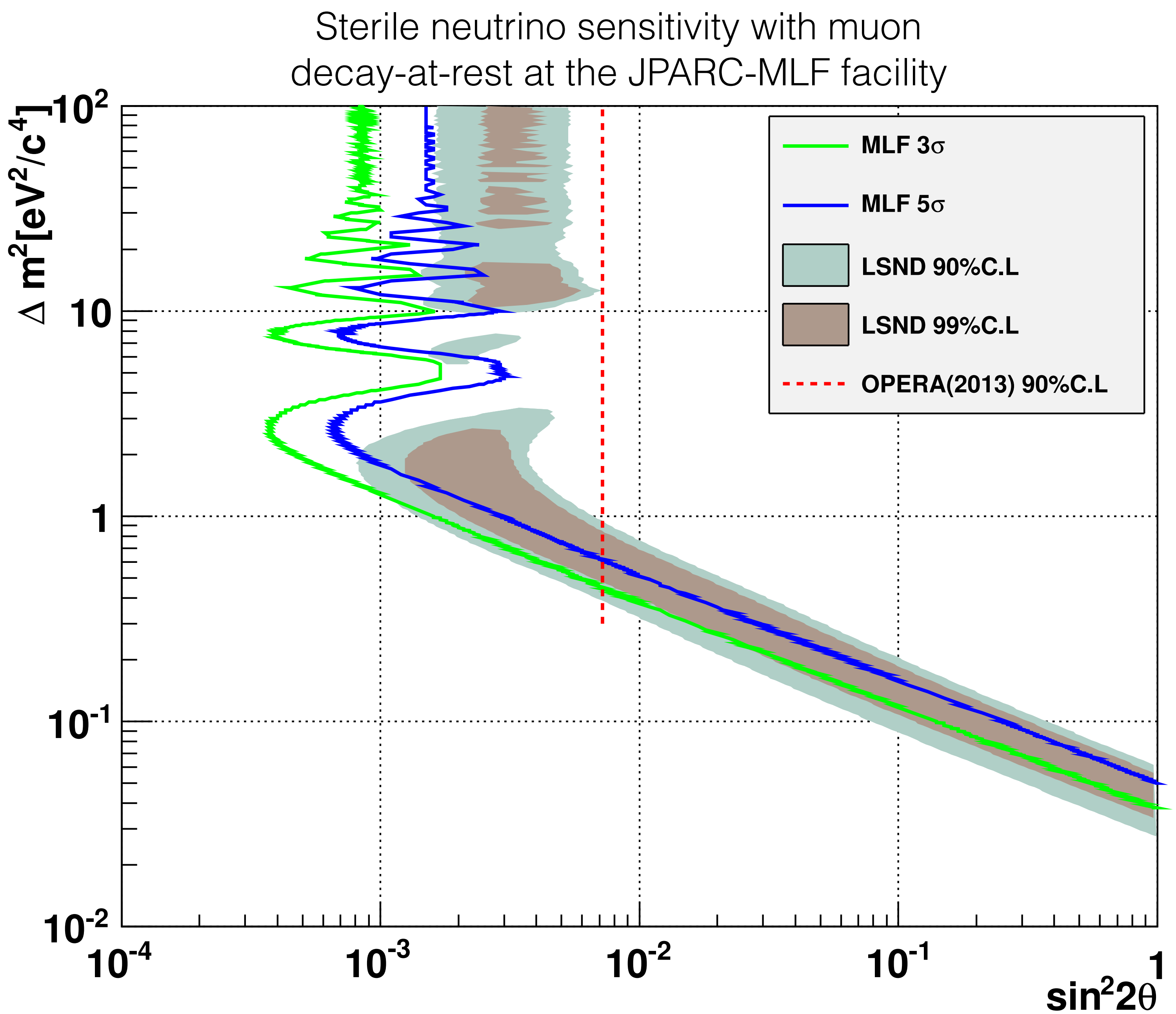
LSND-style

Detect with:
$\overline{\nu}_e p \to e^+ n$



M. Harada *et al*,
arXiv:1310.1437 [physics.ins-det]

JPARC-P56 sensitivity

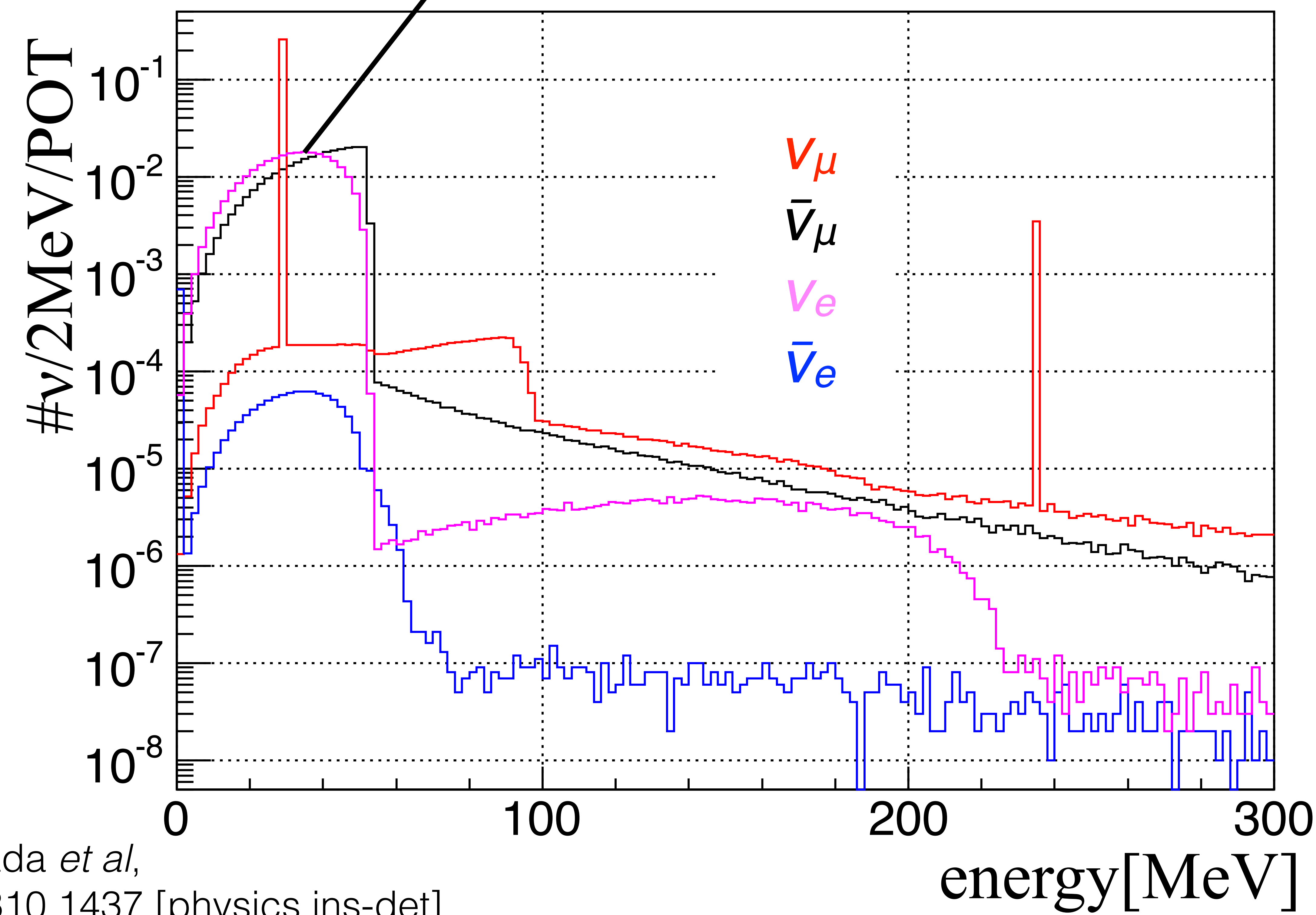


"Phase 1"

Electron disappearance

Detect with:
$\nu_e \ ^{12}C \to e^- \ ^{12}N_{gs}$

$\nu_e \to \nu_{\not e}$?



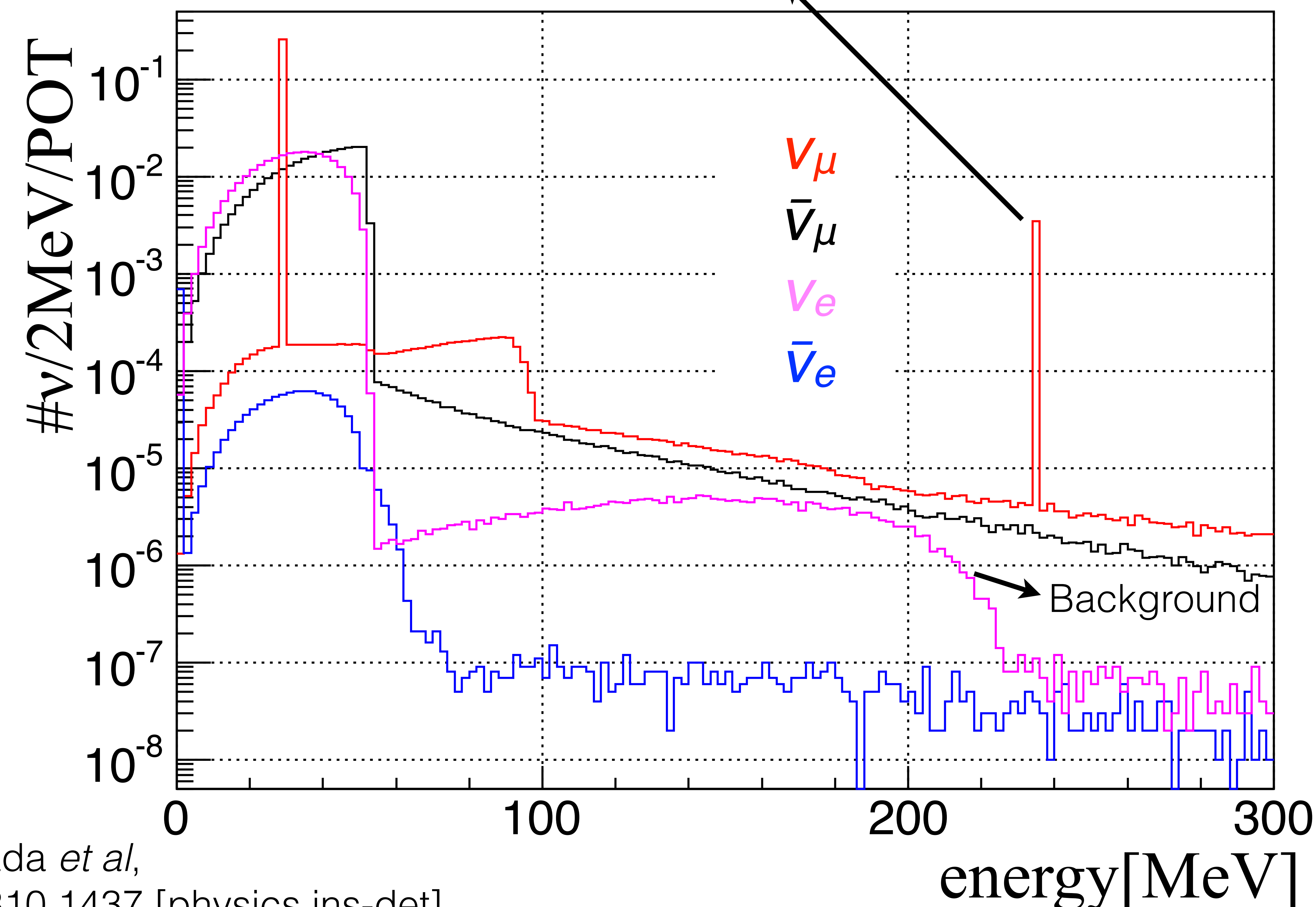
M. Harada *et al*,
arXiv:1310.1437 [physics.ins-det]

Kaon decay-at-rest

Phys. Rev. D 85 093020 (2012)

Detect with:
$\nu_e n \to e^- p$

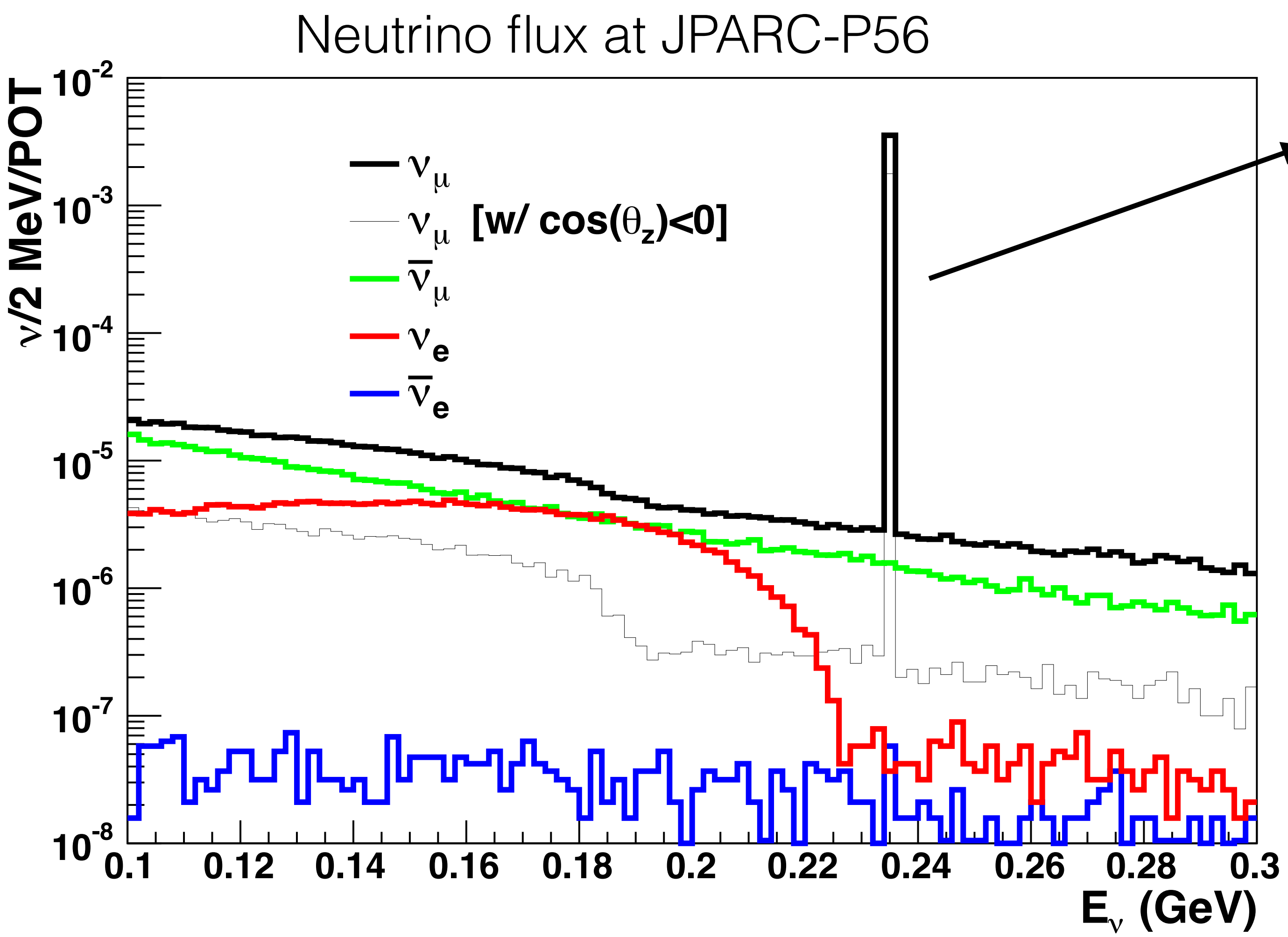
$\nu_\mu \to \nu_e$?



M. Harada *et al*,
arXiv:1310.1437 [physics.ins-det]

Cross section measurements with monoenergetic muon neutrinos

$$K^+ \to \mu^+ \nu_\mu$$



Phys. Rev. D 89 073007 (2014)

This unique neutrino can be used to provide a set of cross section measurements at a known-energy.

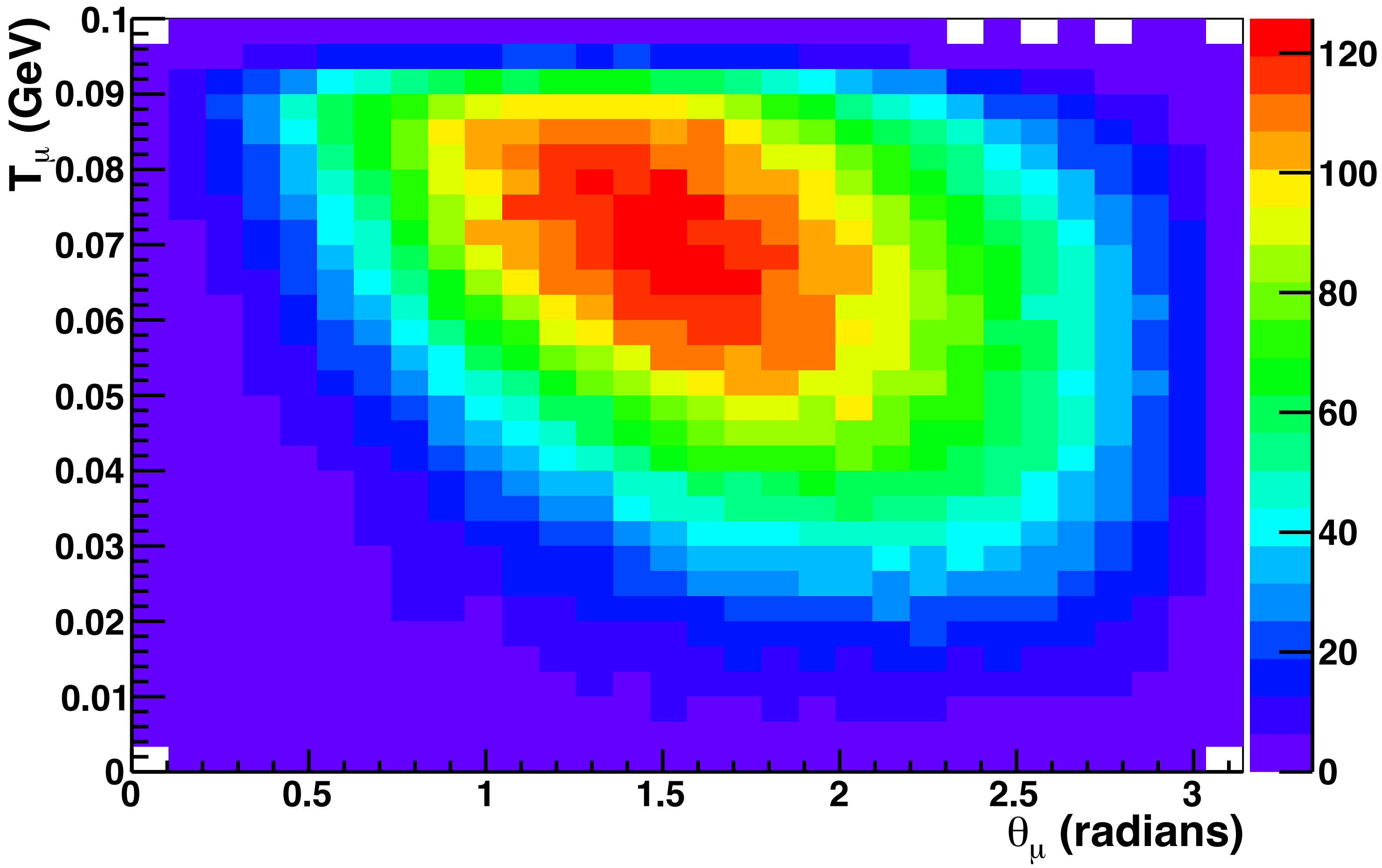
- Reducing systematics associated with long baseline near/far comparison.
- Neutrino as a probe of the nucleus.
  - For the first time ever, we can probe the nucleus with a known-energy (muon) neutrino.

Cross section measurements with monoenergetic muon neutrinos

- The 236 MeV muon neutrino can provide differential cross sections in muon angle and kinetic energy for a known neutrino energy. This “standard candle” would be unprecedented.

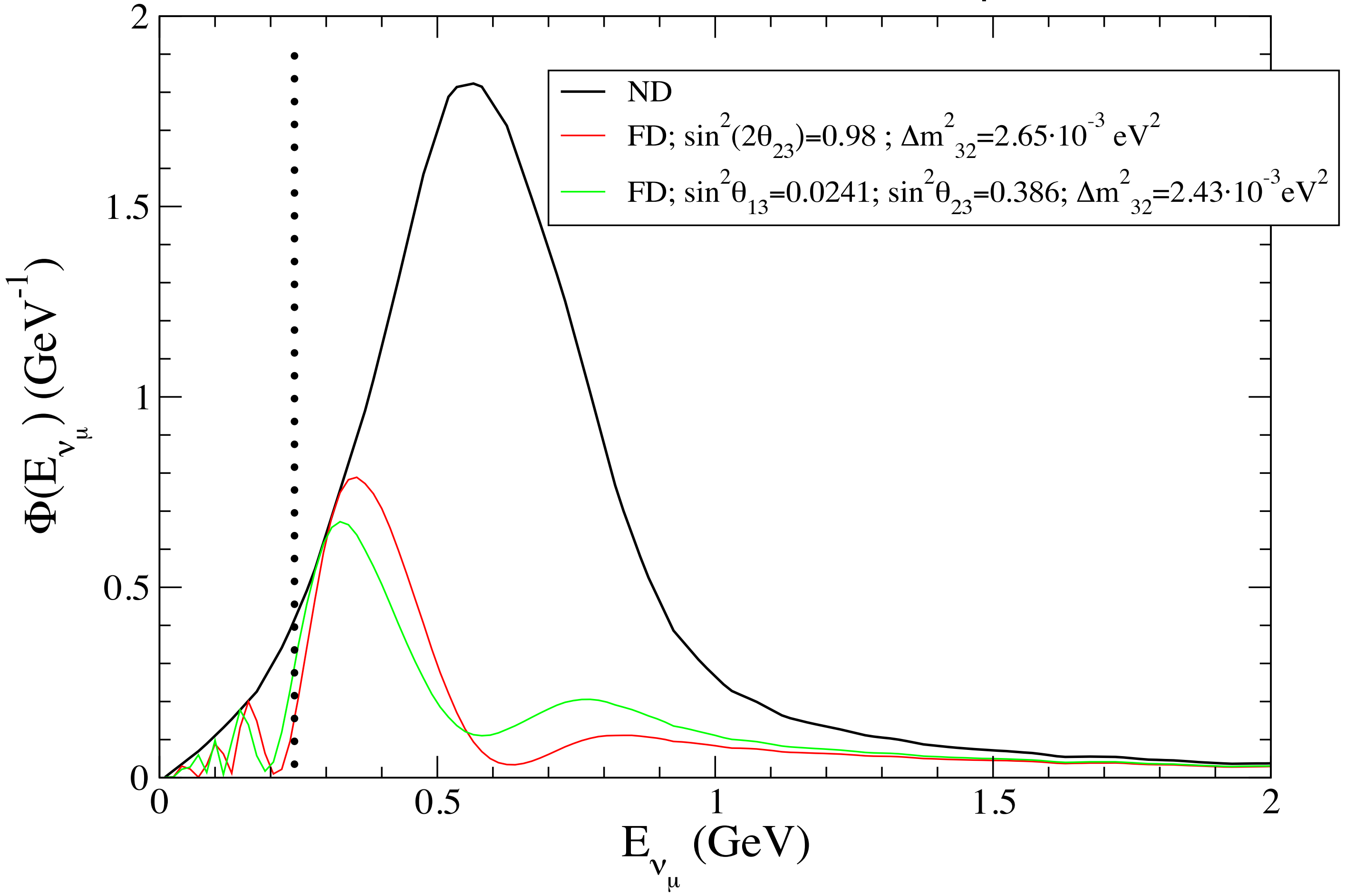
- This is especially relevant for those experiments which solely rely on muon kinematics for reconstructing the neutrino energy.

Phys. Rev. D 89 073007 (2014)

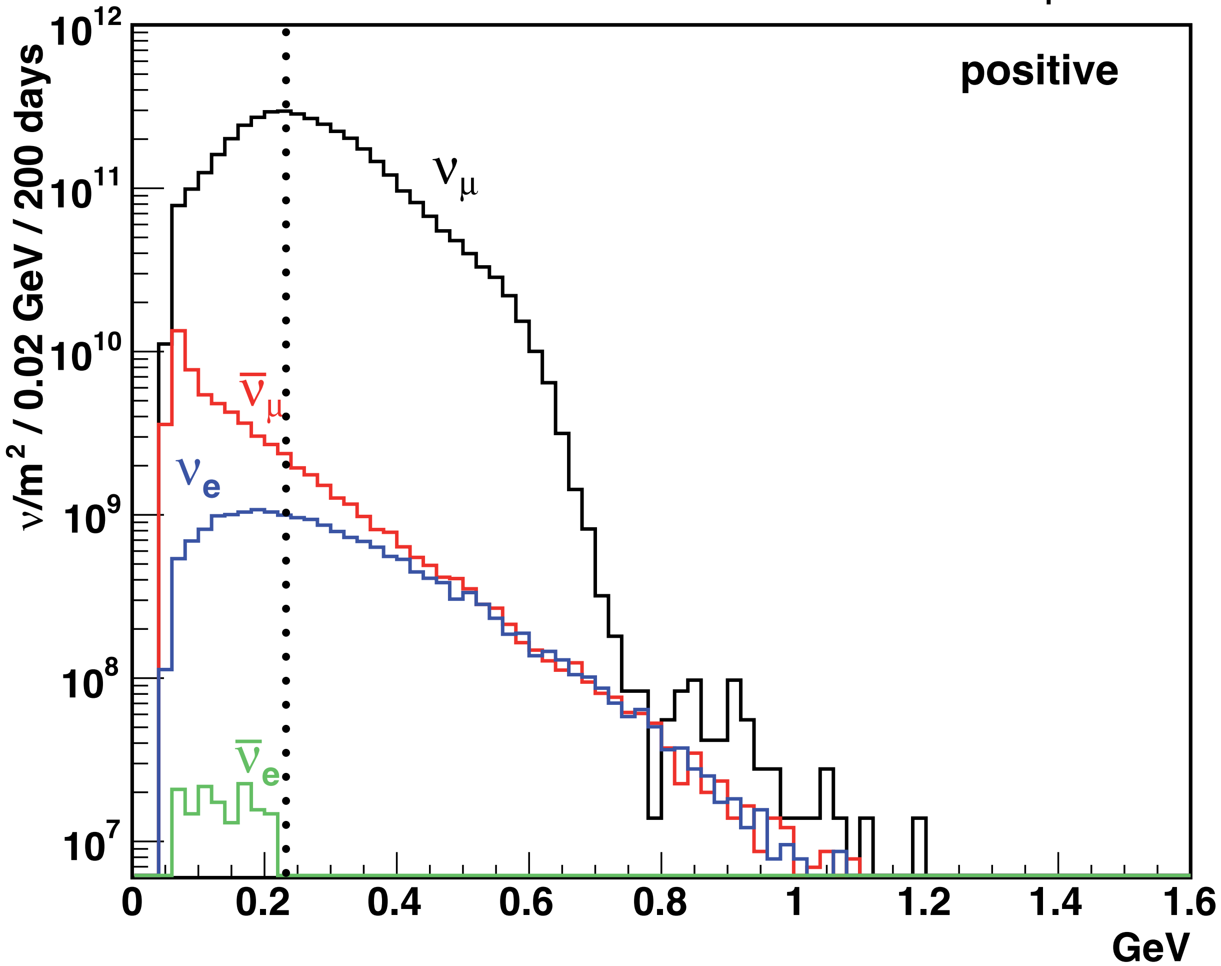


Direct relevance to future CP violation searches

T2K: δ_{CP} search in Japan

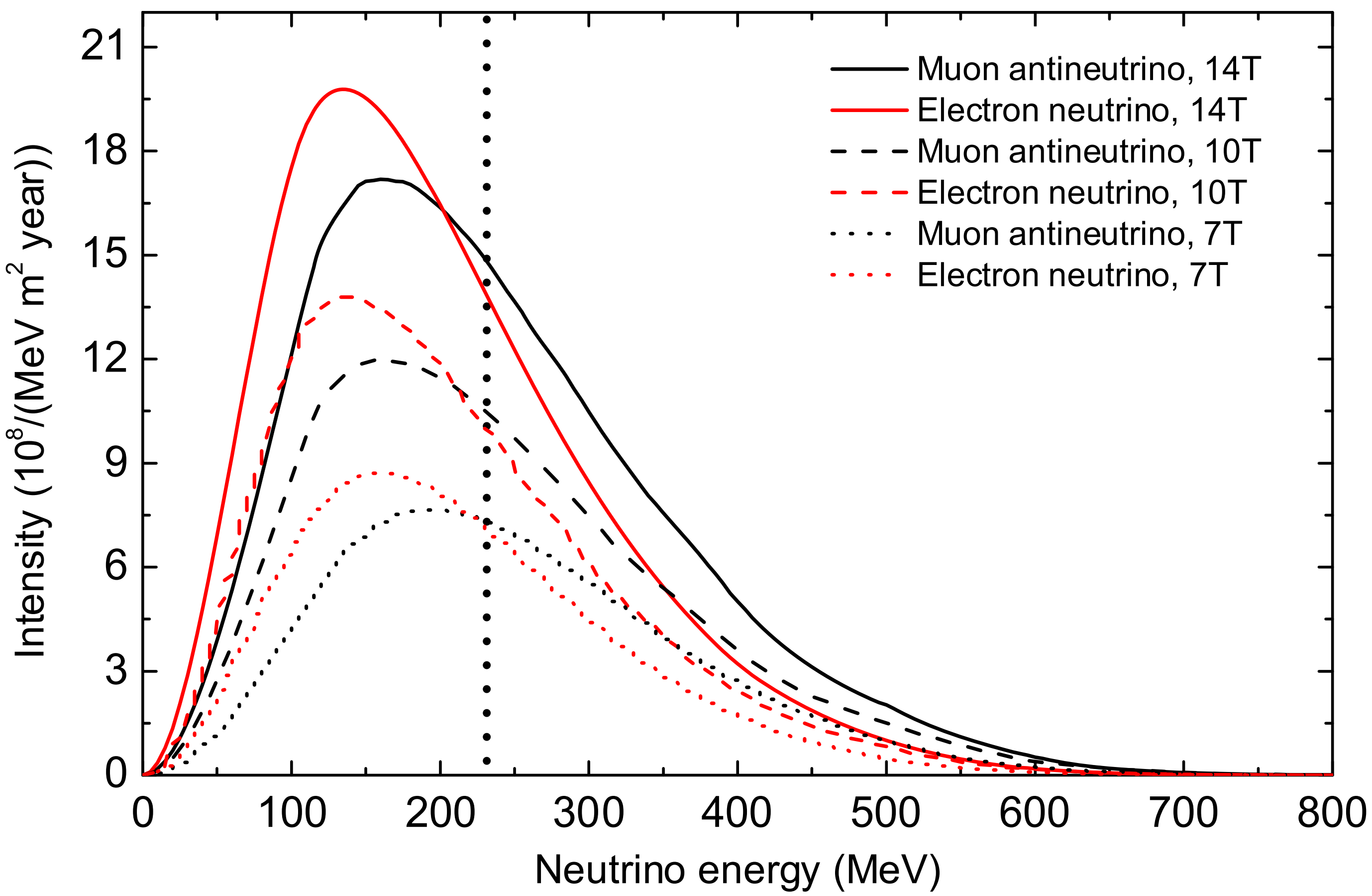


ESSνSB: δ_{CP} search in Europe

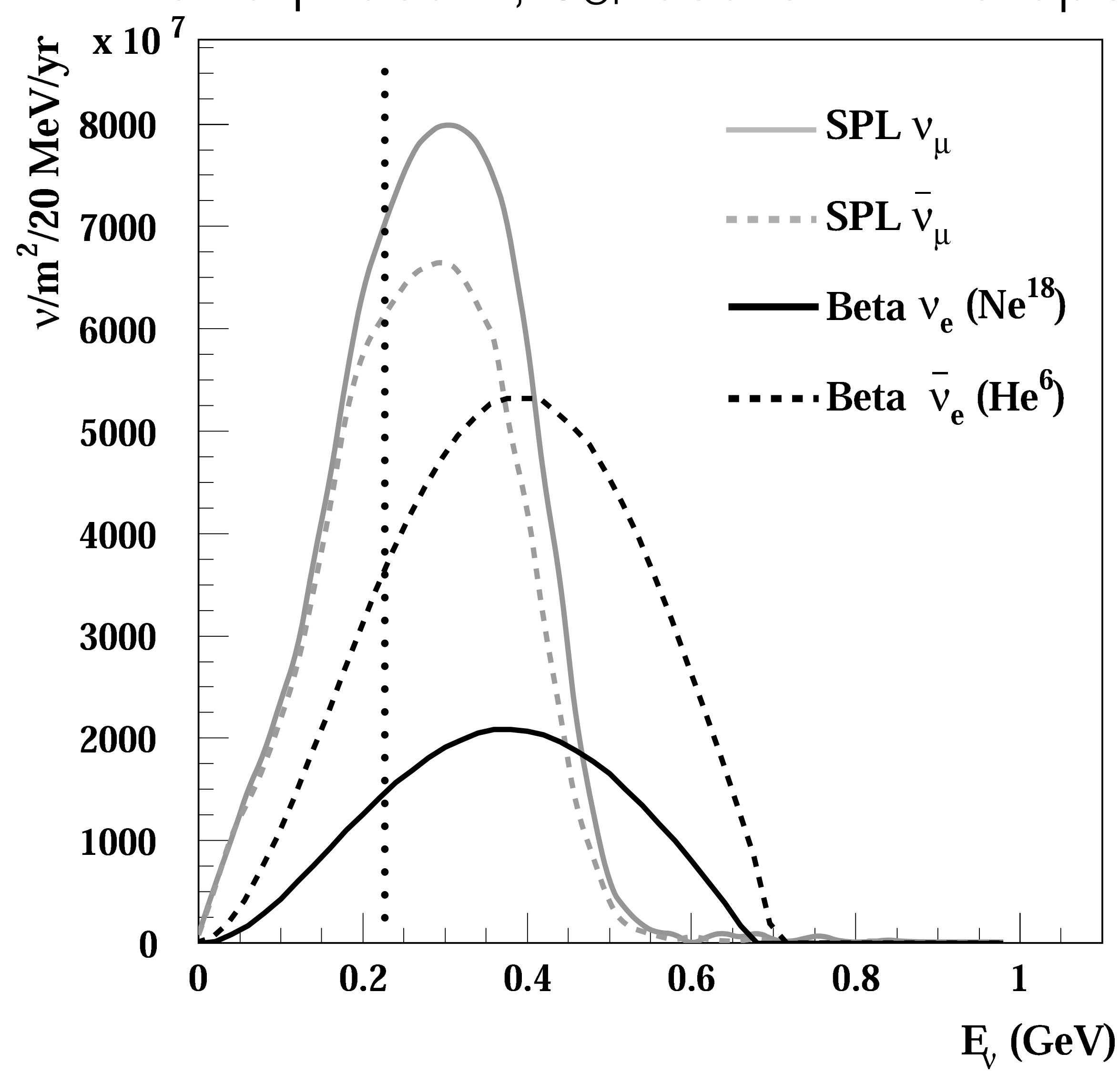


Direct relevance to future CP violation searches

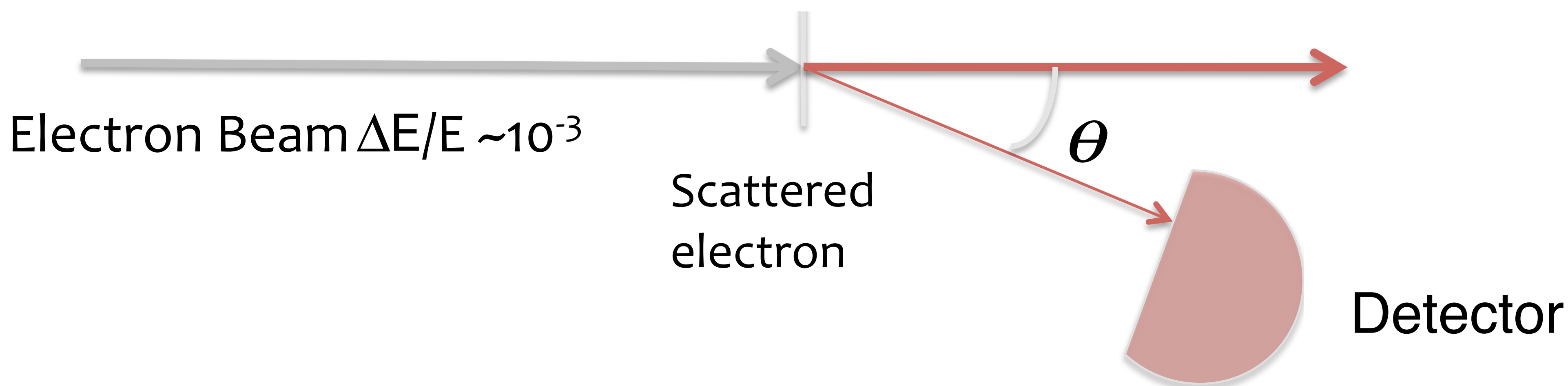
MOMENT; δ_{CP} search in China

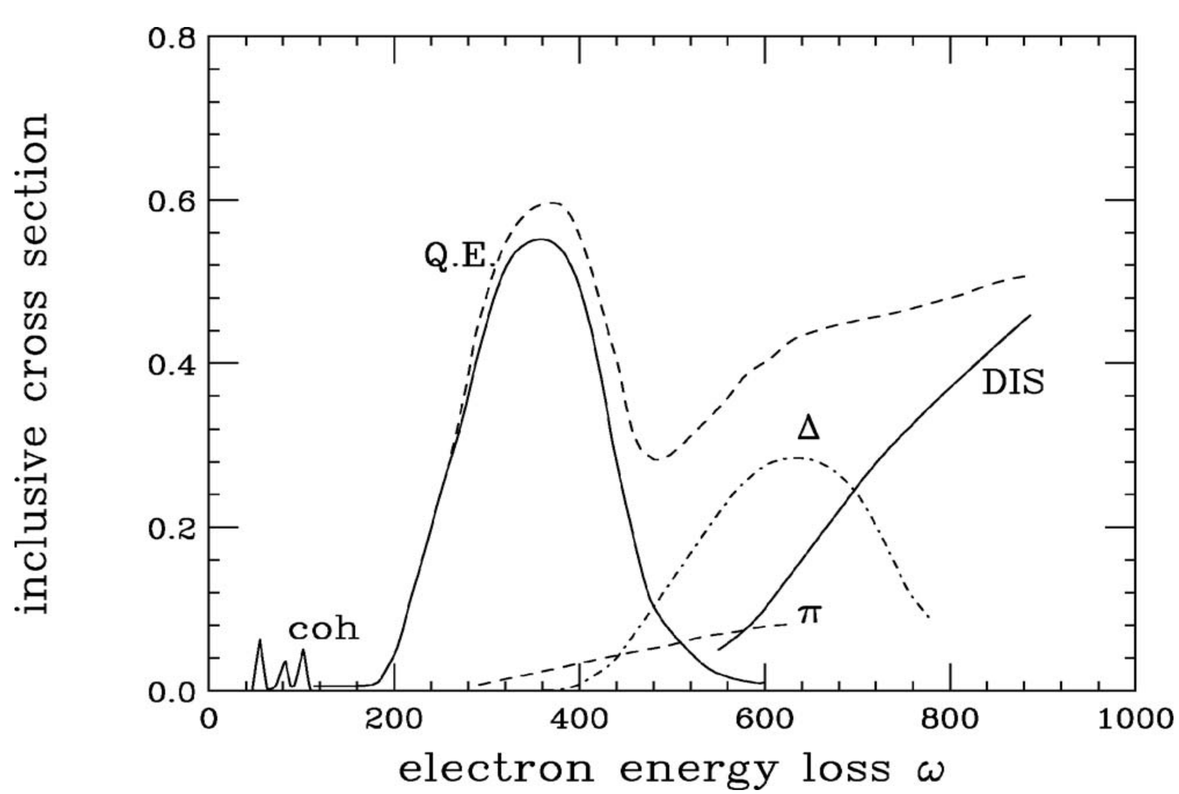


CERN Super Proton Linac and β-beam; δ_{CP} search in Europe



Probing the nucleus





$$(E,0,0,p),\ \ (E',p'\sin\theta,0,p'\cos\theta)$$

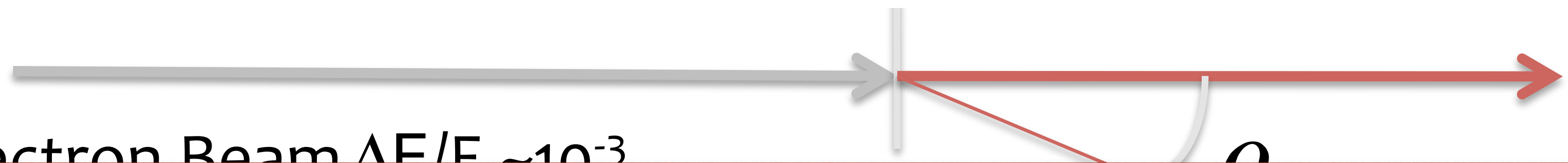
$$\omega \equiv E - E'$$

$$\vec{q} = \vec{p} - \vec{p}\,'$$

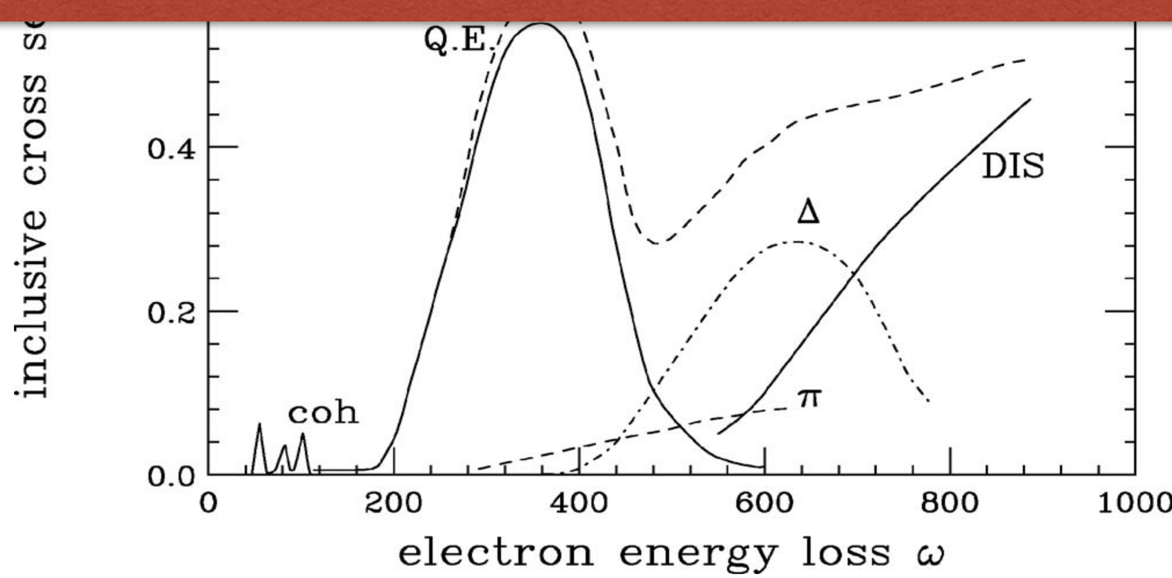
Thus q and ω are precisely known <u>without any reference to the nuclear final state</u>

Slide adapted from G. Garvey

Probing the nucleus



Not possible with neutrinos…until now!



$(E,0,0,p),\ \ (E',p'\sin\theta,0,p'\cos\theta)$

$$\omega \equiv E - E'$$

$$\vec{q} = \vec{p} - \vec{p}\,'$$

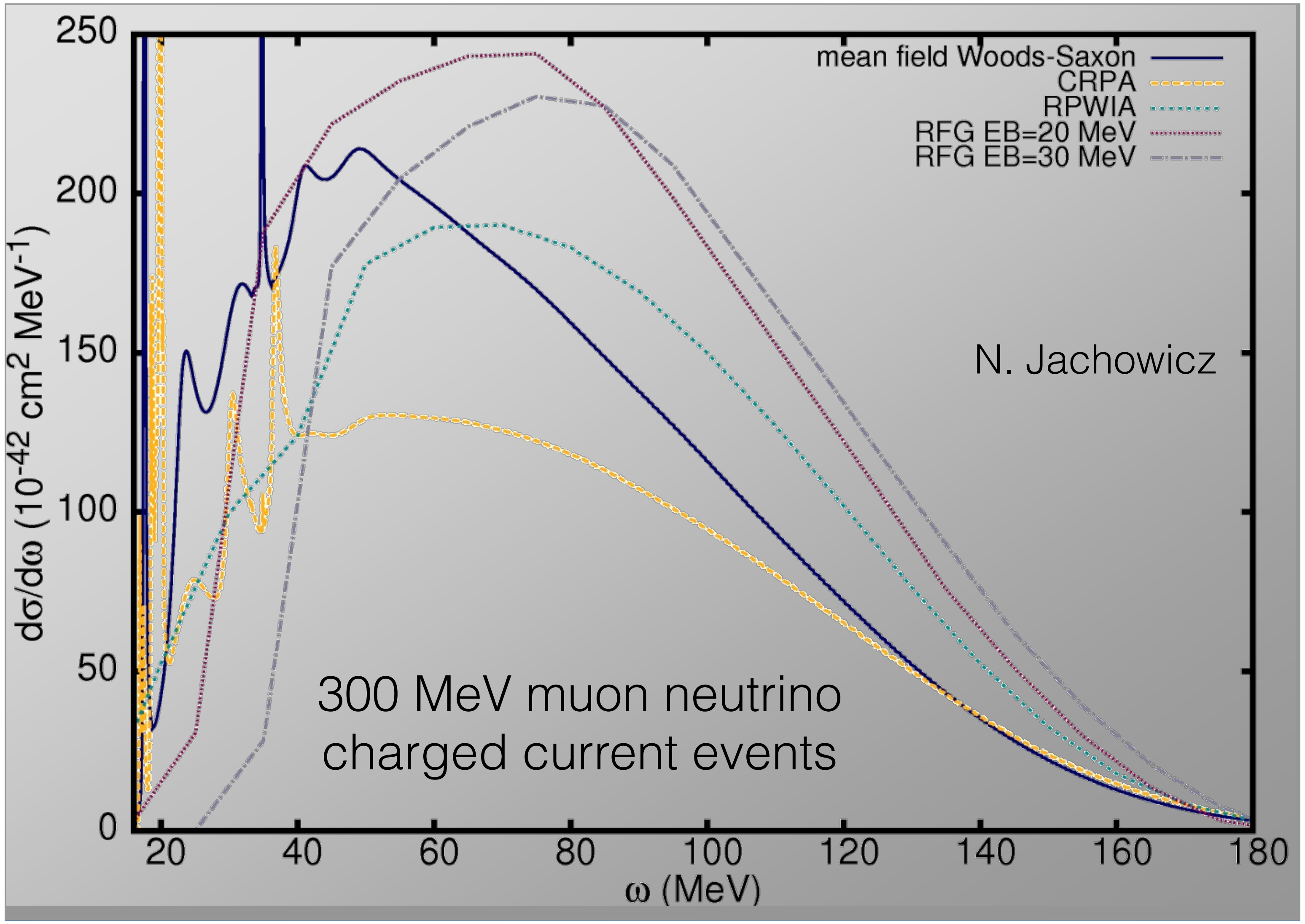
Thus q and ω are precisely known <u>without any reference to the nuclear final state</u>

Slide adapted from G. Garvey

Neutrinos as a nuclear probe

Phys. Rev. D 89 073007 (2014)

- For the first time, we can make these measurements with neutrinos!
- A known-energy, purely weak interacting probe of the nucleus.



}Various ways to treat the nucleus

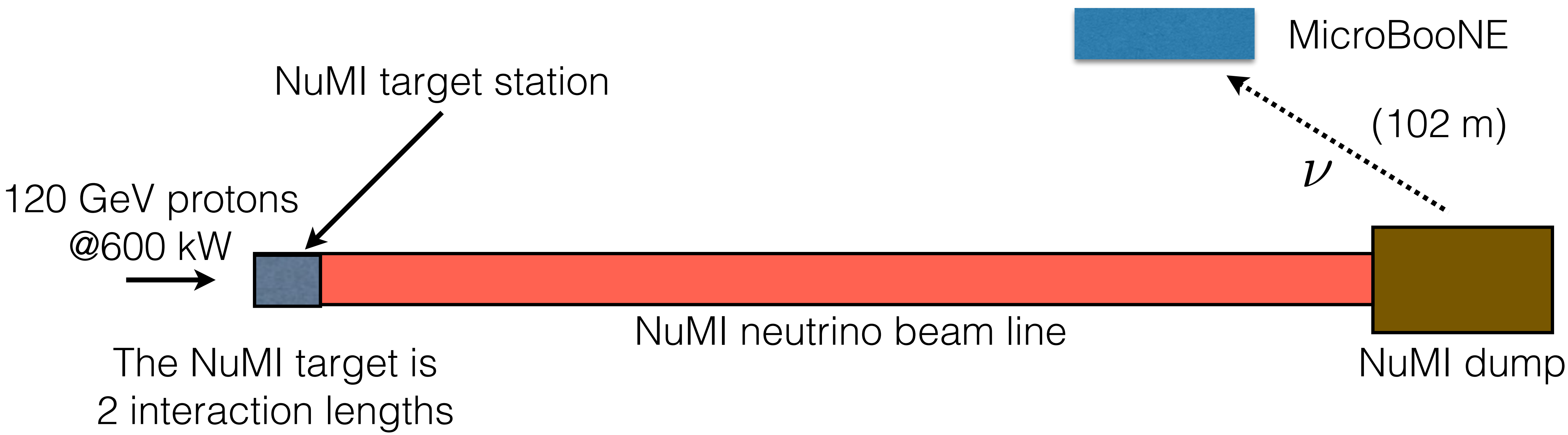
Which model of the nucleus, relevant for neutrinos, is correct?

Kaon decay-at-rest at JPARC-P56

Detector (source)	Target (mass)	Exposure	Distance	236 MeV ν_μ CC	100-225 MeV ν_e CC
Liq scint (JPARC-MLF)	Gd-LS (50 ton)	1.2E23 POT (4 years)	17 m	194000	6500

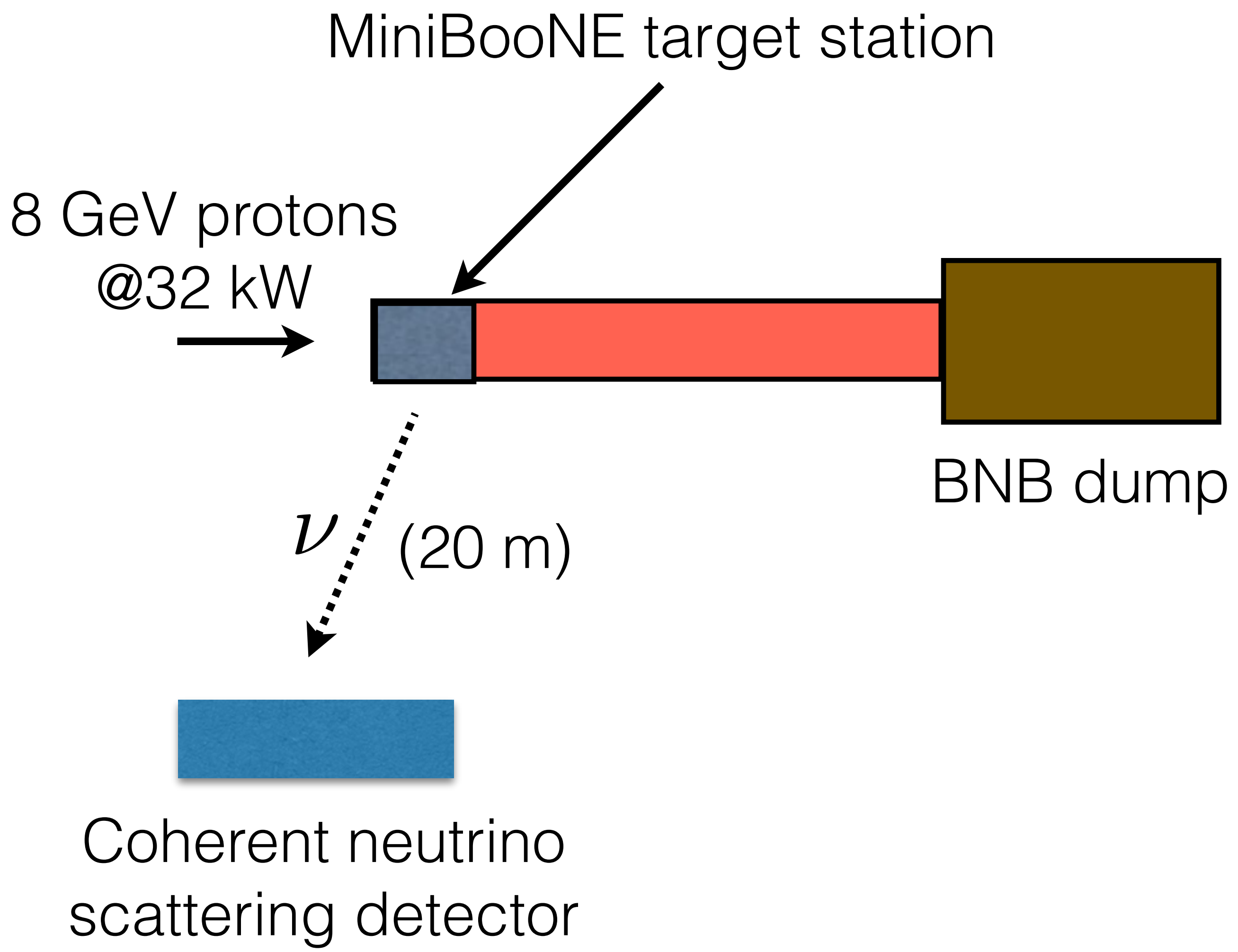
The *actual* distance is "to be determined"

Decay-at-rest at FNAL 1



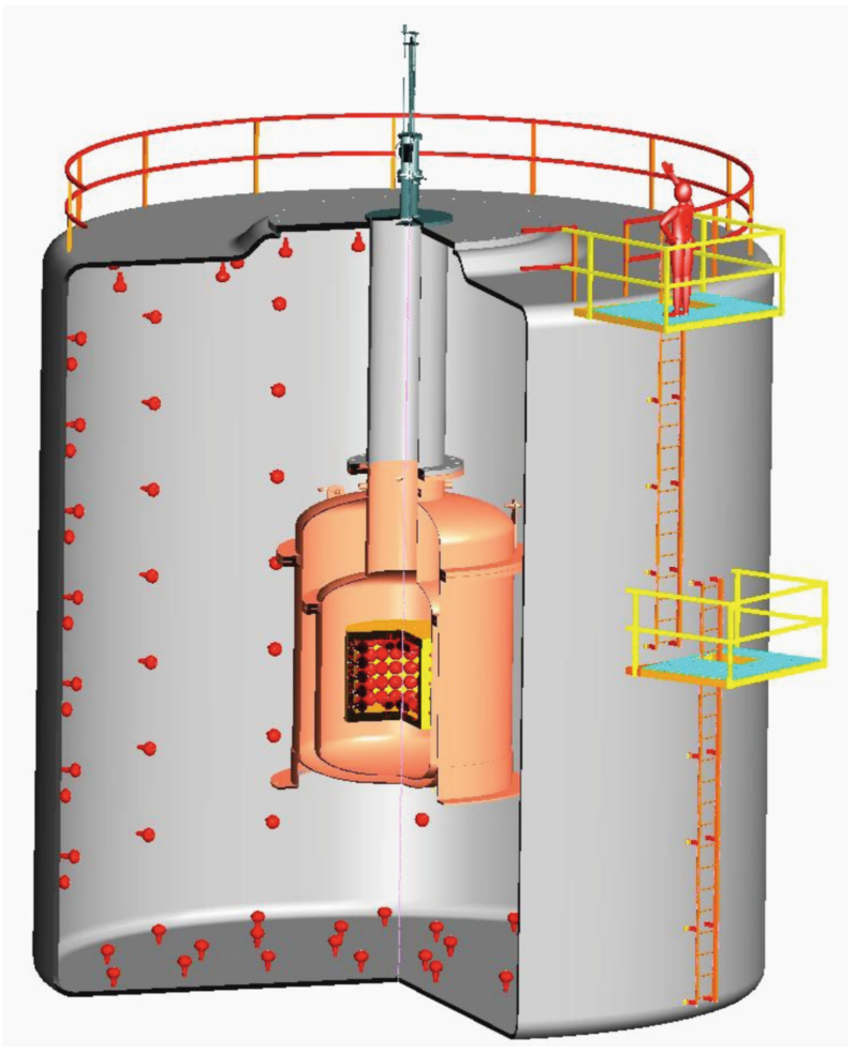
Detector (source)	Target (mass)	Exposure	Distance	236 MeV ν_μ CC
MicroBooNE (600 kW NuMI off-axis)	LAr (90 ton)	1.2E21 POT (2 years)	102 m	2300

Decay-at-rest at FNAL 2



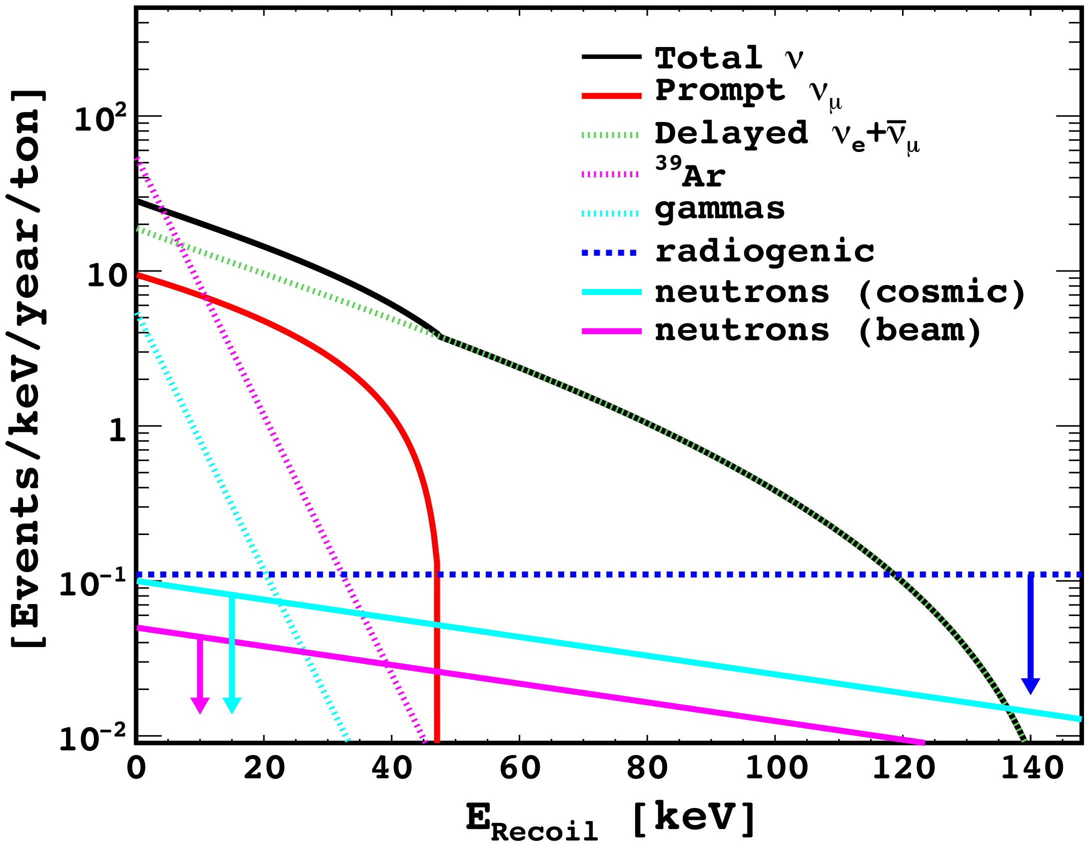
Coherent neutrino detection at Fermilab

A ton-scale LAr detector may perform the first ever observation of the coherent-NCvAS at Fermilab



Envisioned experimental setup

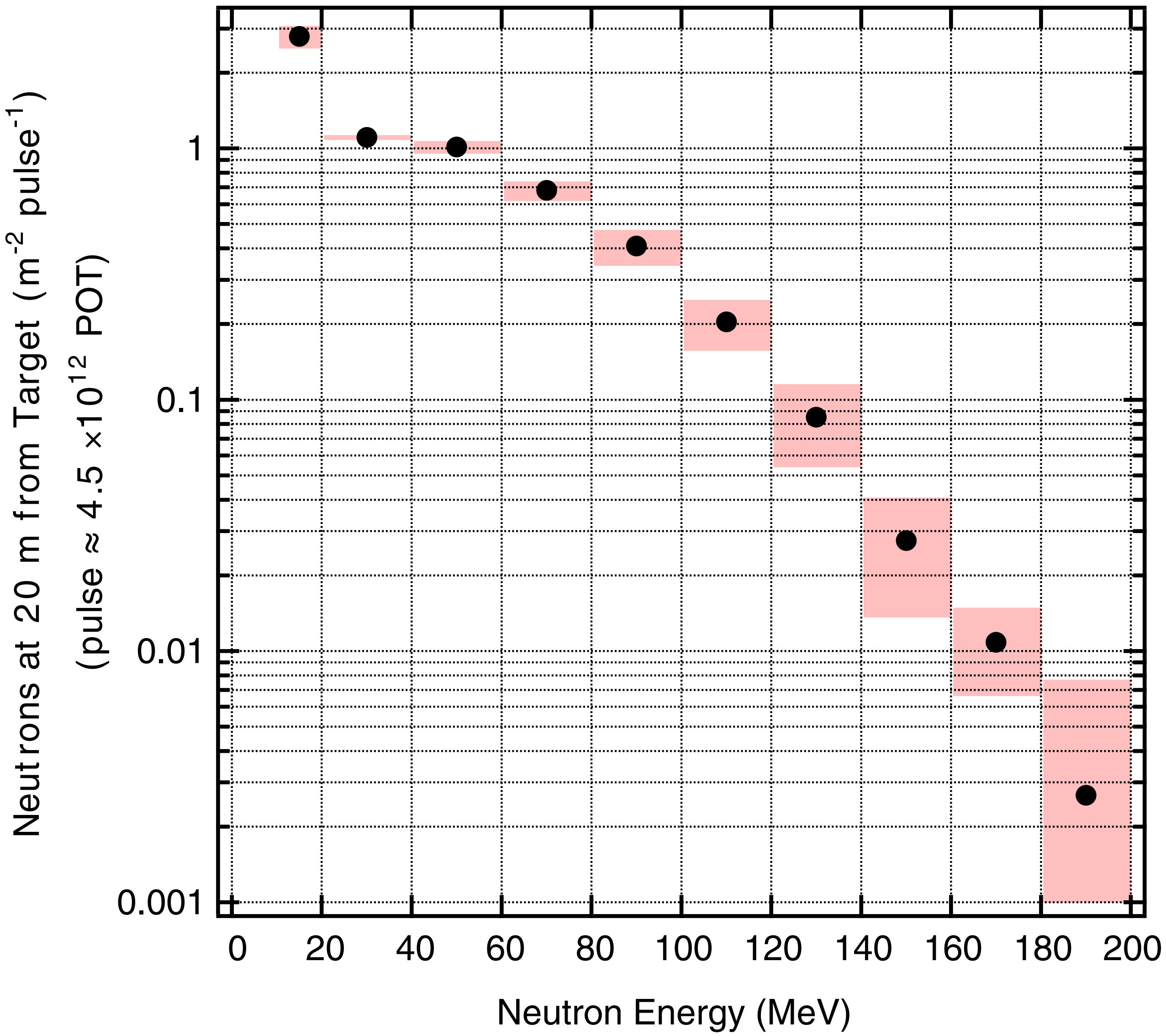
- There is a decay-at-rest neutrino component to the Booster Neutrino Beam, dominating at far-off-axis.
- A WIMP-detector-like single-phase Ar-based device could collect ~200 events/ton/yr at 20 m from the target.



Event rate 20 m from BNB target

Phys. Rev. D 89 072004 (2014)

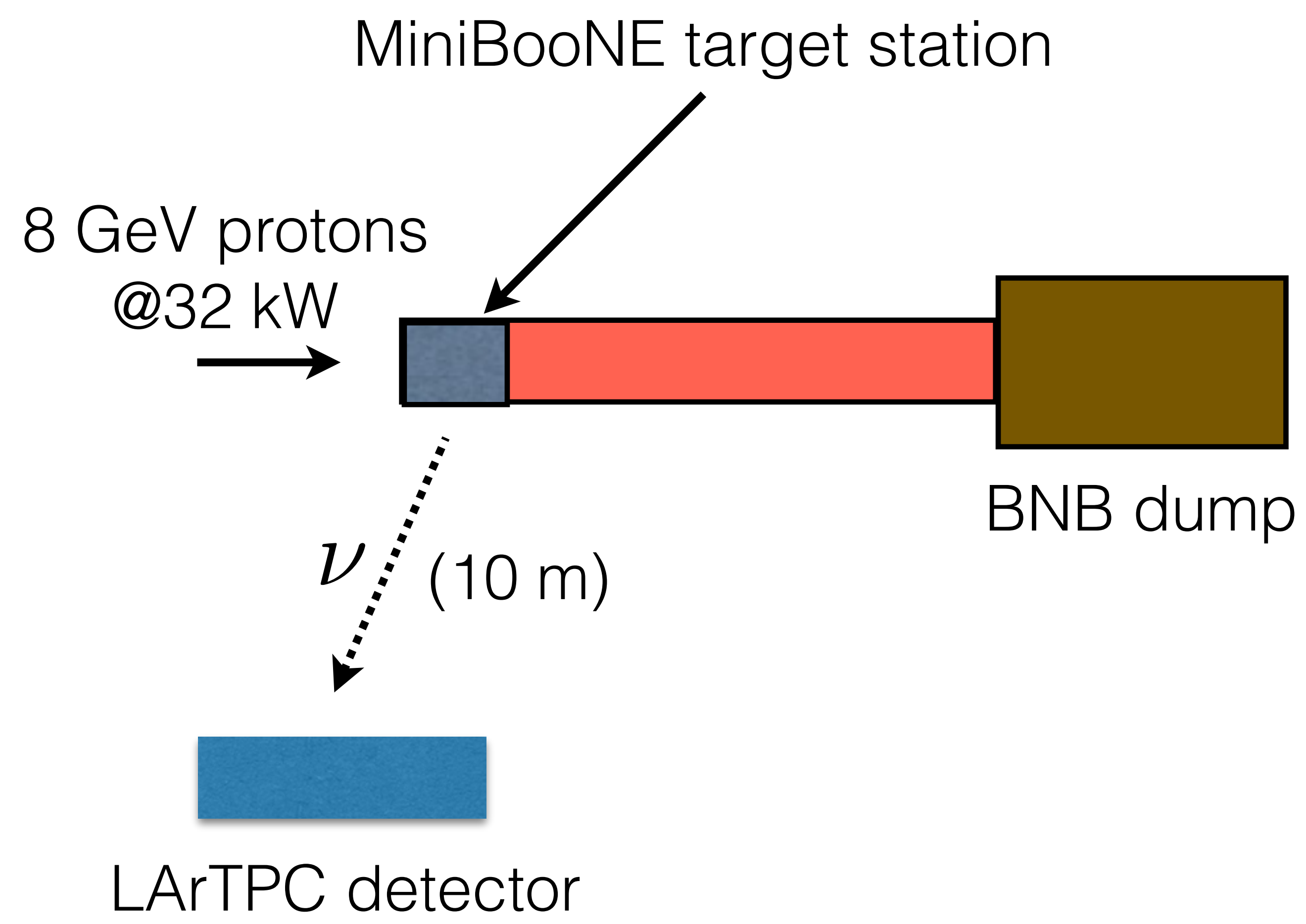
Is neutron background at the BNB ok?



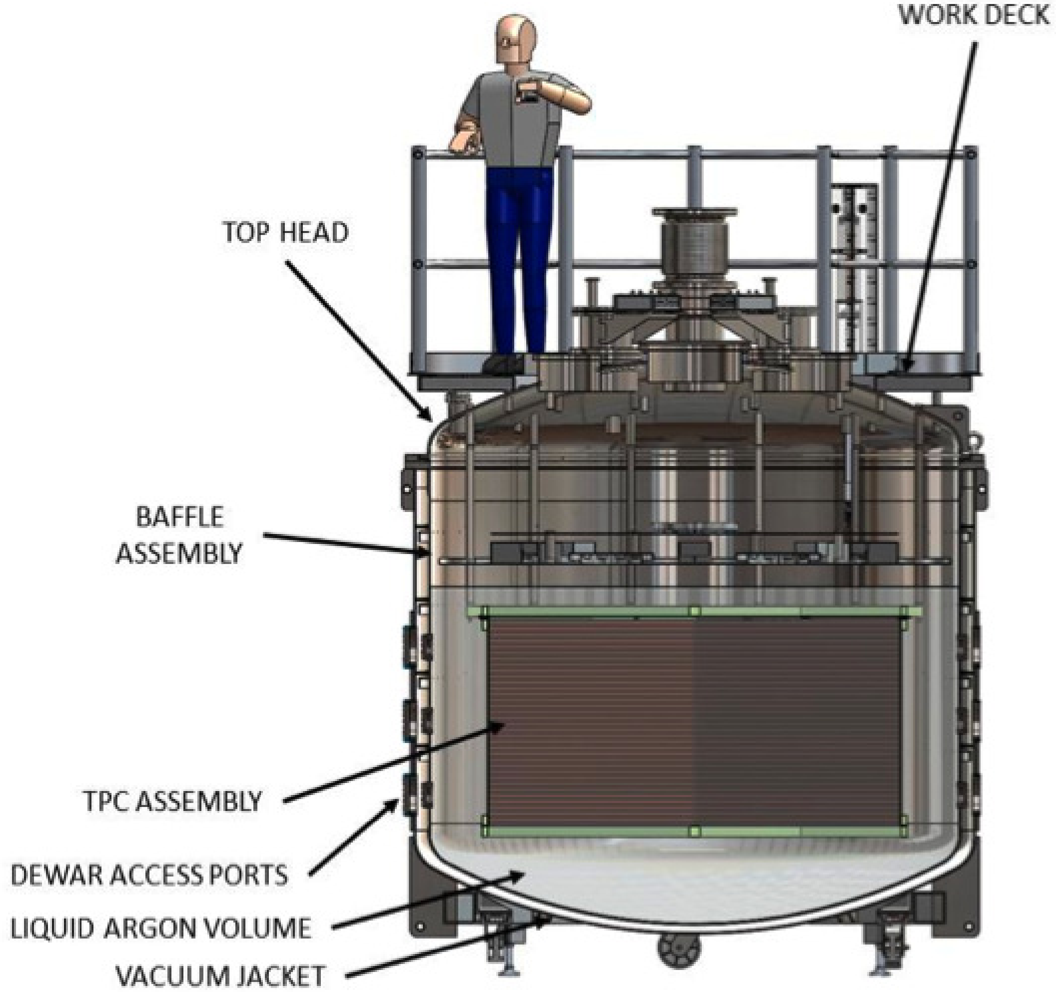
Phys. Rev. D 89 072004 (2014)

- Yes.
- The fast neutron background has been measured using the SciBATH detector (82 L of liquid scintillator).

Decay-at-rest at FNAL 3

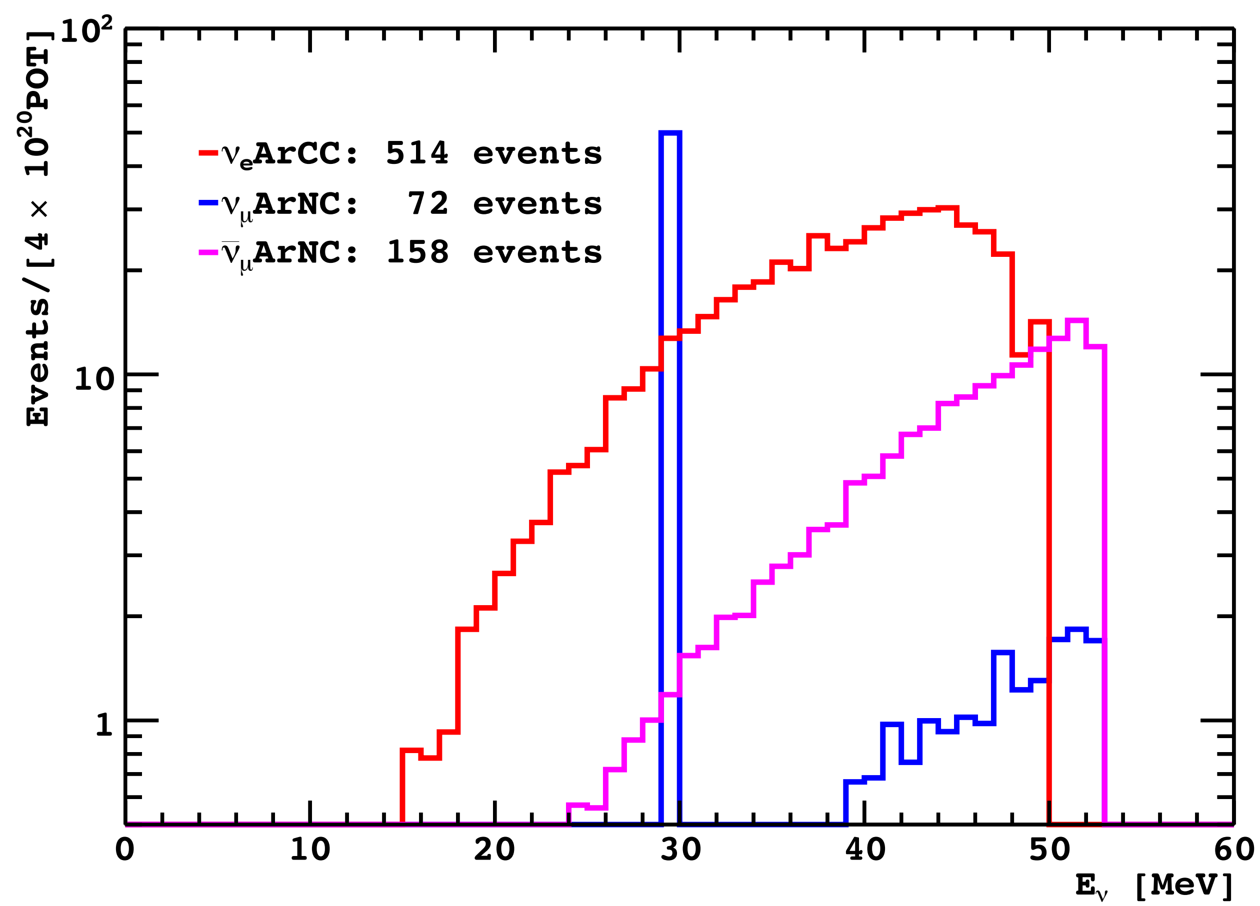


CAPTAIN at the BNB



CAPTAIN BNB LOI to PAC

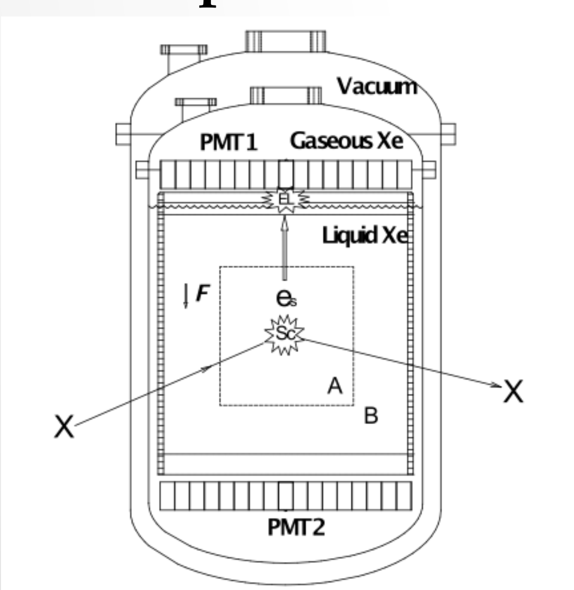
- Proposal to measure pion/muon decay-at-rest neutrinos at FNAL's BNB (10 m from target).
- Mainly relevant for supernova neutrinos and understanding neutrino-Ar xsec at low energies.
- May bring CAPTAIN to SNS after BNB?



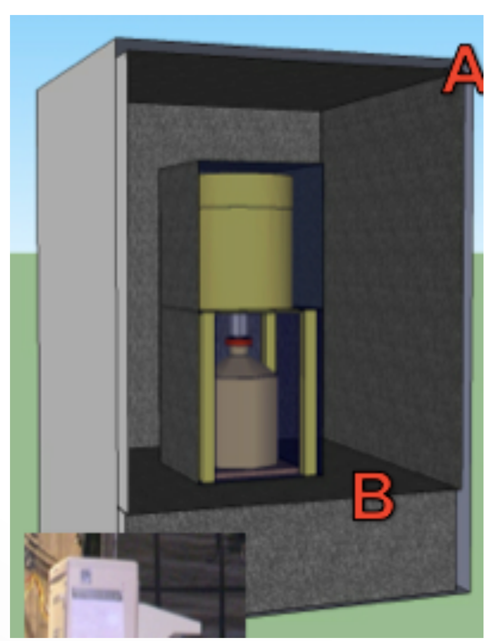
COHERENT at the SNS

- COHERENT experiment at the SNS
  - Low threshold detector development (synergies with nuclear, astro, …)
  - Coherent neutrino measurements
  - First neutrino results expected this year!
- Three technologies in first-phase deployment.

Two-phase LXe



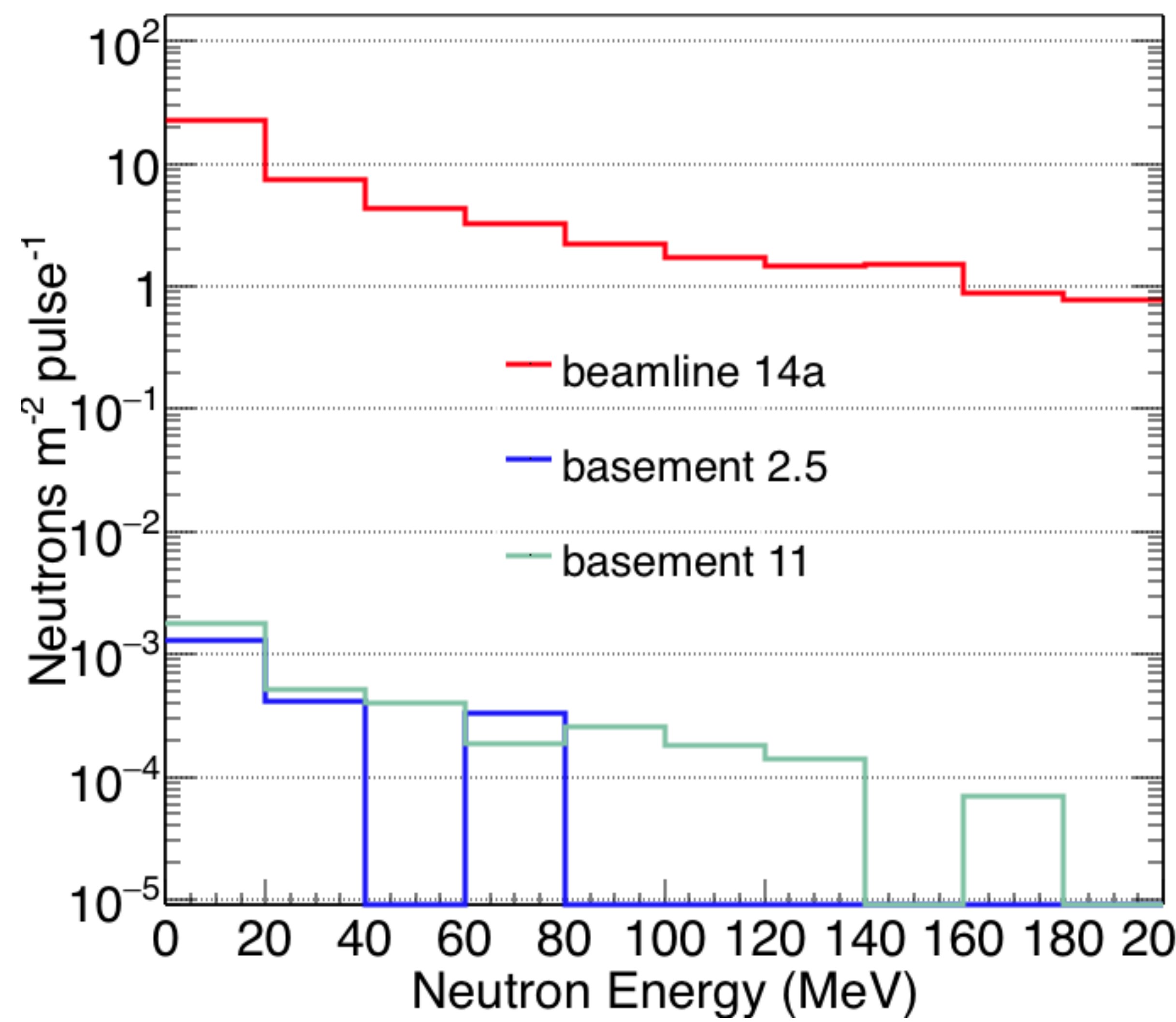
HPGe PPC



CsI

Is neutron background at the SNS ok?

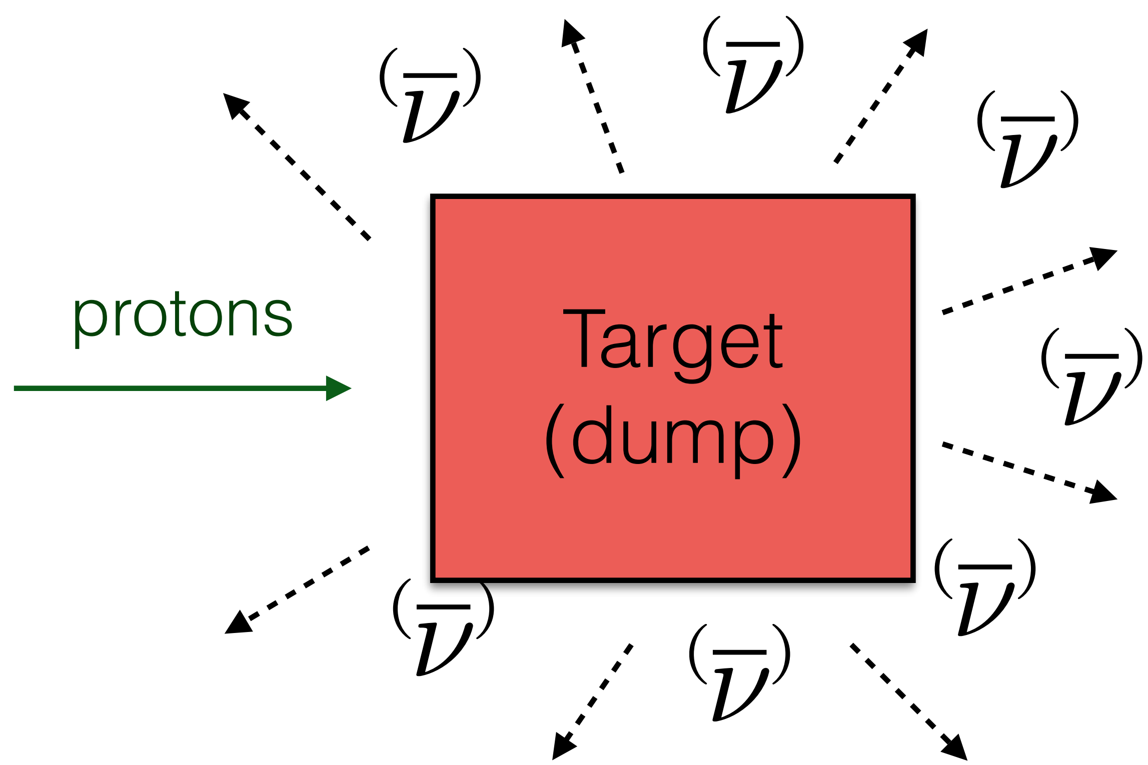
- Yes.
- The fast neutron and cosmogenic backgrounds at various locations near the SNS have been well characterized by the COHERENT collaboration.
- These measurements are relevant for COHERENT and OscSNS.
- The neutron background is so low in the “basement” locations that the shielding requirements for COHERENT are quite modest.



Thanks to H. Ray!

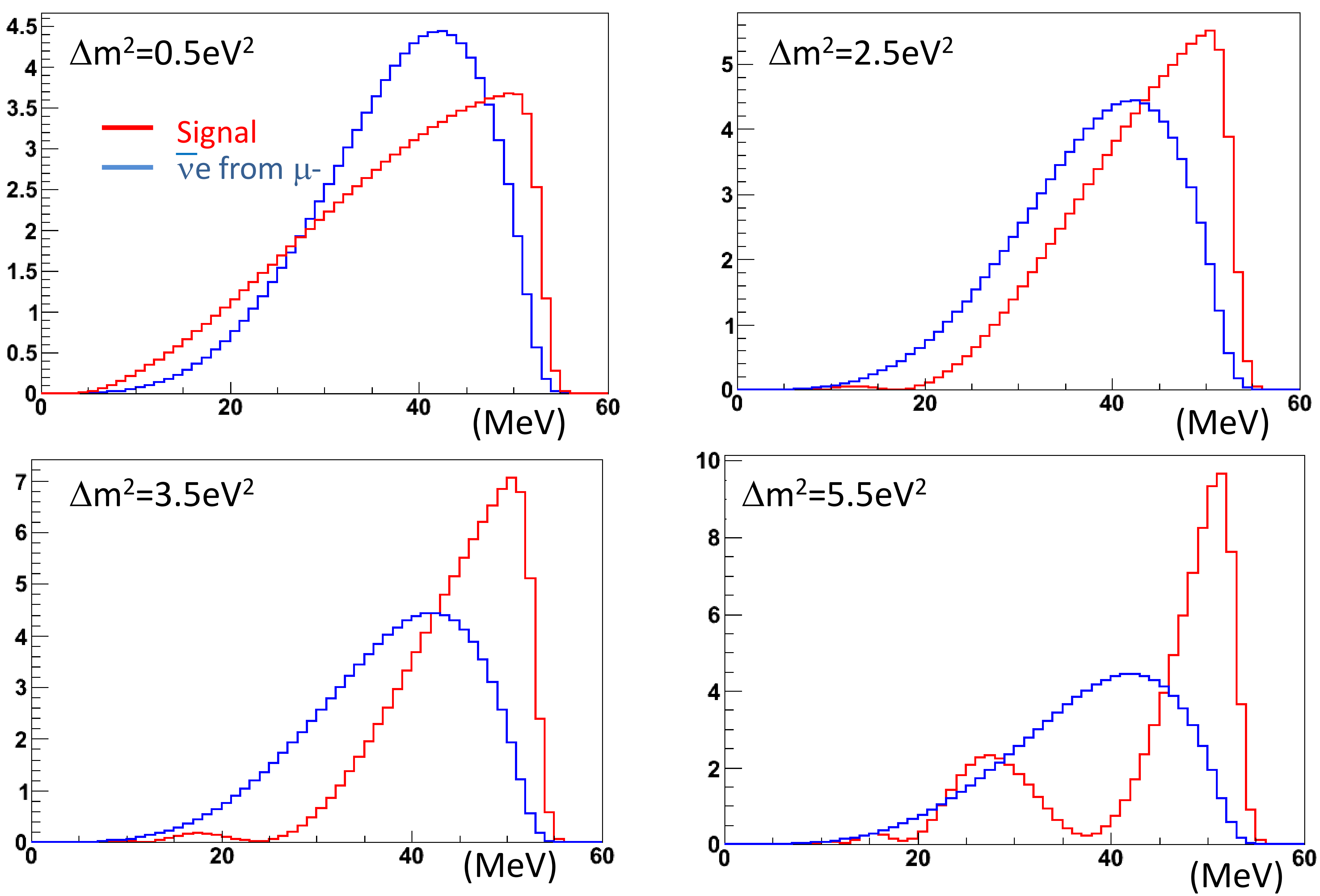
Conclusions

- There are many efforts worldwide to take advantage of pion/muon and kaon decay-at-rest neutrinos.
- These are some of the best neutrinos out there…and many of our existing sources are in need of a detector!



Backup

A comment on the $\overline{\nu}_e$ intrinsic background for LSND-style experiments

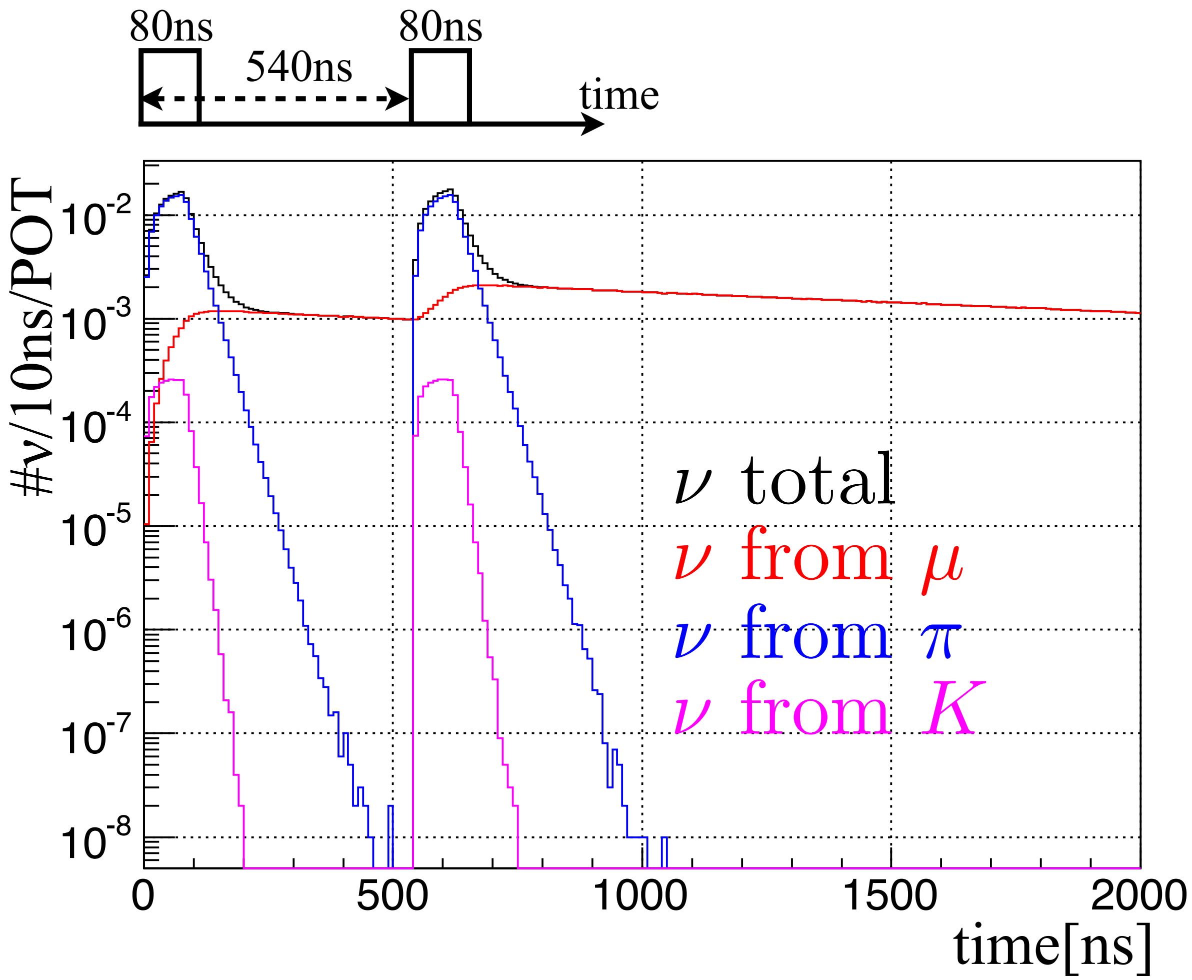


(plots are normalized by area)

M. Harada *et al*, arXiv:1310.1437 [physics.ins-det]

JPARC-P56

	OscSNS	JPARC-MLF (phase 1)	Notes
Detector	800 ton	50 ton	
Baseline	60 m	~20 m (TBD)	
Cost	$20M	$5M	
Beam kinetic energy	1 GeV	3 GeV	pi+/pi- ratio is less favorable for JPARC-P56
Beam power	1.4 MW	1 MW (eventually)	
Beam pulse	695 ns, 60 Hz	80 ns (x2), 25 Hz	Difference doesn't matter much due to muon lifetime



M. Harada *et al*, arXiv:1310.1437 [physics.ins-det]

IsoDAR cost estimates at present

Cost-effective design options for IsoDAR
A. Adelmann et al. arXiv:1210.4454

1st source constructed -> $30M base cost (2013 $)

If more sources are constructed: $15M each

recommended contingency as of now: 50%
after first engineering design: 20%

DOE-sponsored study on a 2 mA proton machine

COST / BENEFIT COMPARISON

FOR

45 MEV AND 70 MEV CYCLOTRONS

MAY 26, 2005

Conducted for:

U.S. Department of Energy
Office of Nuclear Energy, Science, and Technology
Office of Nuclear Facilities Management
19901 Germantown Road
Germantown, MD 20874

Conducted by:

JUPITER
Technical, Security, and Management Solutions

Suite 900, Westfield North
2730 University Boulevard West
Wheaton, MD 20902

This is a simpler machine.

IsoDAR will cost more because the machine is larger…but this sets the scale.

EXECUTIVE SUMMARY

A cost/benefit study was conducted by *JUPITER* Corporation to compare acquisition and operating costs for a 45 MeV and 70 MeV negative ion cyclotron to be used by the Department of Energy in the production of medical radioisotopes. The study utilized available information from Brookhaven National Laboratory (BNL) in New York and from the University of Nantes in France, since both organizations have proposed the acquisition of a 70 MeV cyclotron. Cost information obtained from a vendor, Advanced Cyclotron Systems, pertained only to their 30 MeV cyclotron. However, scaling factors were developed to enable a conversion of this information for generation of costs for the higher energy accelerators.

Two credible cyclotron vendors (IBA Technology Group in Belgium and Advanced Cyclotron Systems, Inc. In Canada) were identified that have both the interest and capability to produce a 45 MeV or 70 MeV cyclotron operating at a beam current of 2 mA (milliamperes).

The results of our analysis of design costs, cyclotron fabrication costs, and beamline costs (excluding building construction costs) resulted in total acquisition costs of:

- $14.8M for the 45 MeV cyclotron, and
- $17.0M for the 70 MeV cyclotron.

Annual operating cost estimates for a 70 MeV cyclotron ranged between $1.9M and $1.1M; the large uncertainty is due to the lack of specificity in available data in comparing costs from BNL and the University of Nantes.

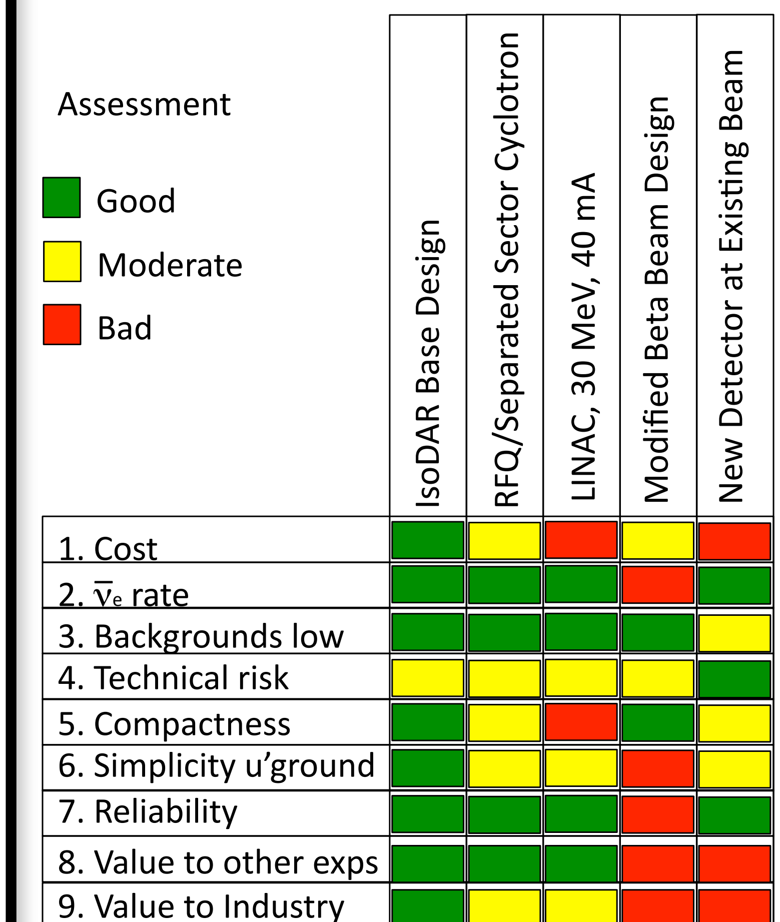
Overall power requirements (exclusive of facility heating and air conditioning) were estimated to be:

- 560 kW for the 45 MeV cyclotron, and
- 831 kW for the 70 MeV cyclotron.

Operational lifetime is expected to be in excess of 30 years for the main components of the accelerator.

Considerable scientific and economic benefits are gained in using the 70 MeV cyclotron compared to use of the 45 MeV cyclotron in terms of the variety and quantity of isotopes that can be produced. Selected examples of benefits in isotope production are discussed.

Other options?



DAEδALUS cost estimates at present

$130M near accelerator, $450M for the 3 sites.
This includes various contingencies, 20% to 50%

Assumes component cost drops by 50% after first production.
Does not include site-specific cost (buildings)

SRC is the cost driver. See: “Engineering study for the DAEdALUS sector magnet”; Minervini et al. arXiv:1209.4886

The RF is based on the PSI design, for which we have a cost.

The similarity to RIKEN allows a cost sanity check. We have a cost for this.

All targets are ~1 MW (similar to existing), noting that each cyclotron can have multiple targets.

For a comparison between DAEδALUS and existing cyclotrons (e.g. RIKEN, TRIUMF, PSI) see: “Multimegawatt DAEδALUS Cyclotrons for Neutrino Physics” arXiv:1207.4895

δ_{CP} sensitivity assumptions

Configuration Name	Source(s)	Average Long Baseline Beam Power	Detector	Fiducial Volume	Run Length
DAEδALUS@LENA	DAEδALUS only	N/A	LENA	50 kt	10 years
DAEδALUS@Hyper-K	DAEδALUS only	N/A	Hyper-K	560 kt	10 years
DAEδALUS/JPARC (nu only)@Hyper-K	DAEδALUS & JPARC	750 kW	Hyper-K	560 kt	10 years
JPARC@Hyper-K	JPARC	750 kW	Hyper-K	560 kt	3 years ν + 7 years $\bar{\nu}$ [3]
LBNE	FNAL	850 kW	LBNE	35 kt	5 years ν 5 years $\bar{\nu}$ [6]

The DAEδALUS group is currently focussed on the injector cyclotron, IsoDAR

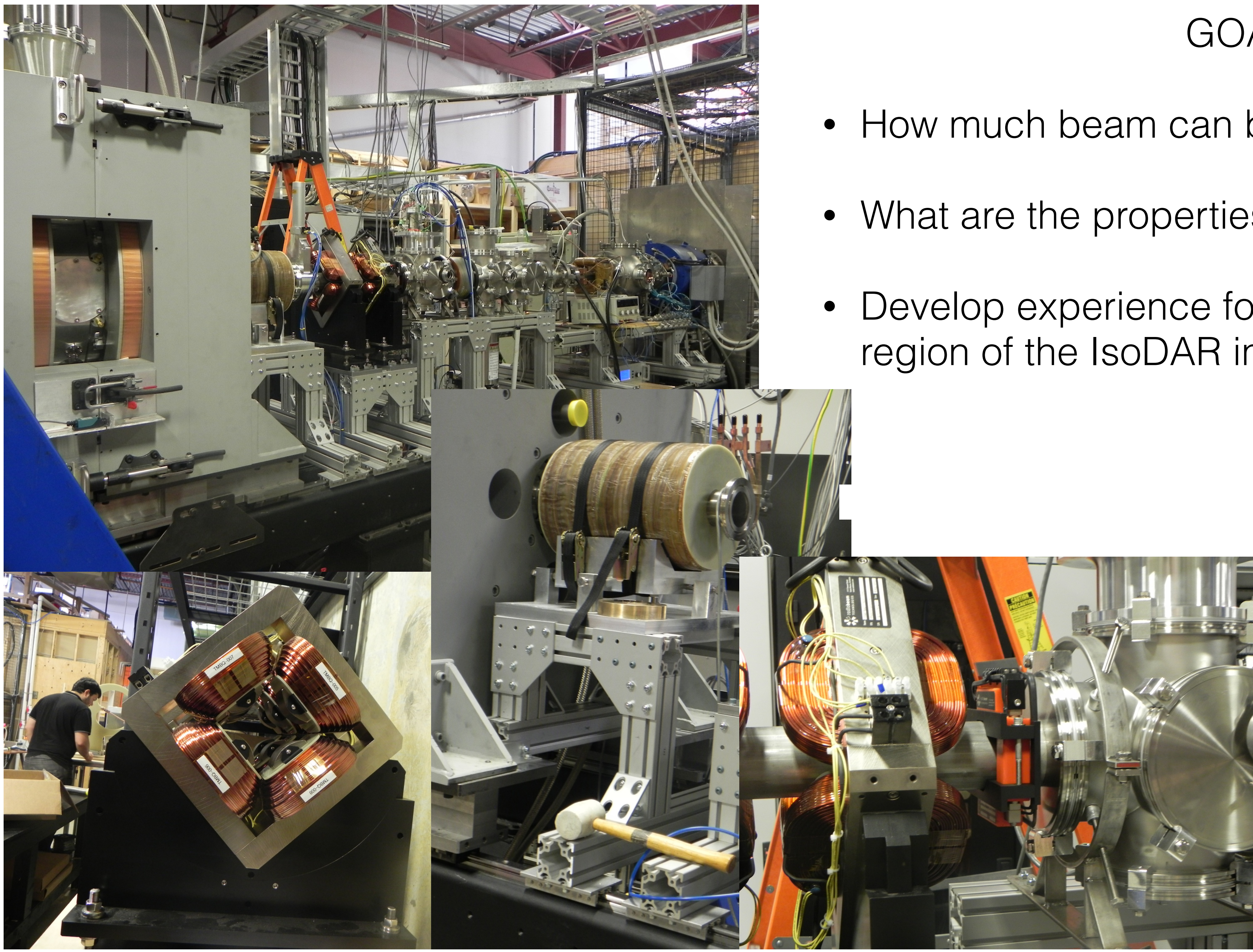
- IsoDAR wants to produce ~10 mA of protons at 60 MeV. Commercial cyclotrons (IBA, BEST) produce ~1 mA of protons at 60 MeV.

How will IsoDAR achieve 10 mA?

Four issues to solve:

1. Space charge.
2. Push the envelope of H_2^+ ion source intensity.
3. Develop an unusually large spiral inflector to get beam in the cyclotron.
4. Avoid beam losses at extraction.

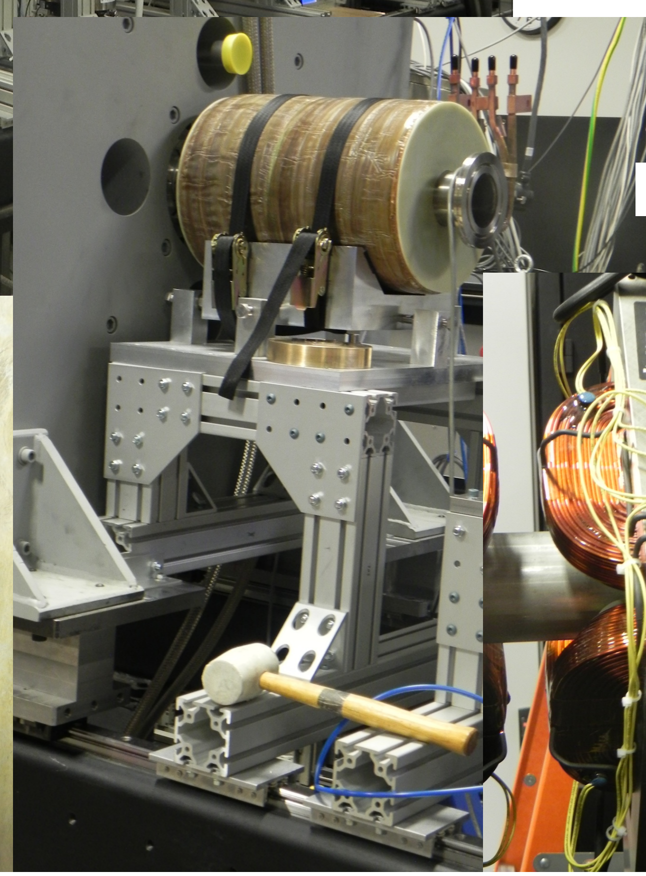
Beam has been characterized at Best Cyclotrons, Inc, Vancouver (Best Cyclotron Systems, INFN-Catania, and MIT -- NSF funded)

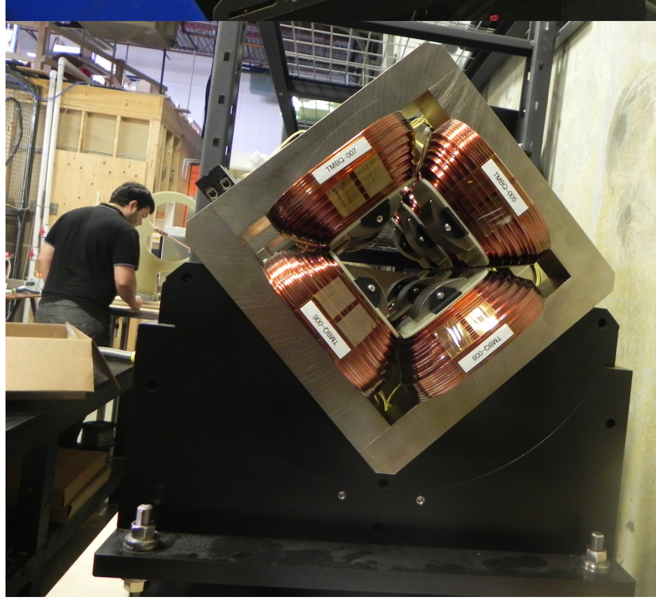


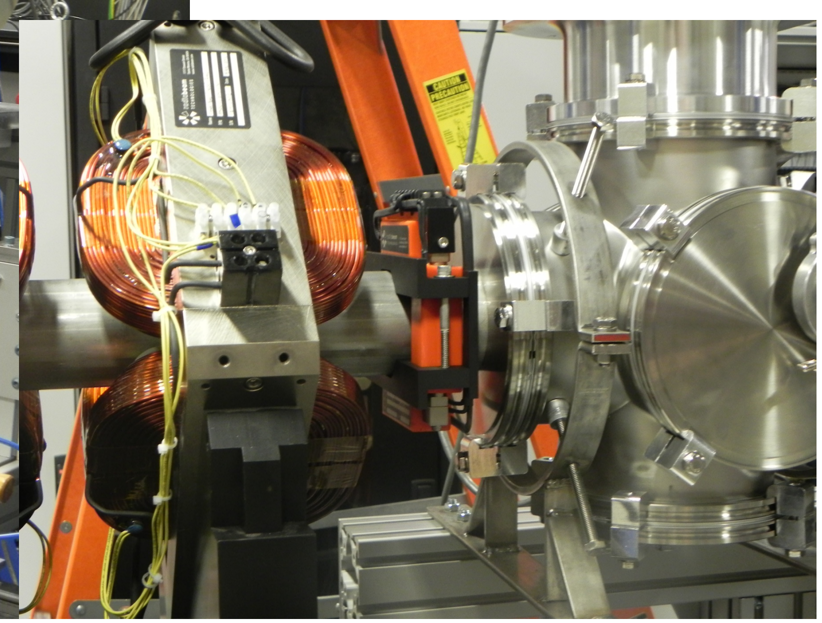
GOALS

- How much beam can be captured?
- What are the properties of the captured beam?
- Develop experience for designing the central region of the IsoDAR injector cyclotron.

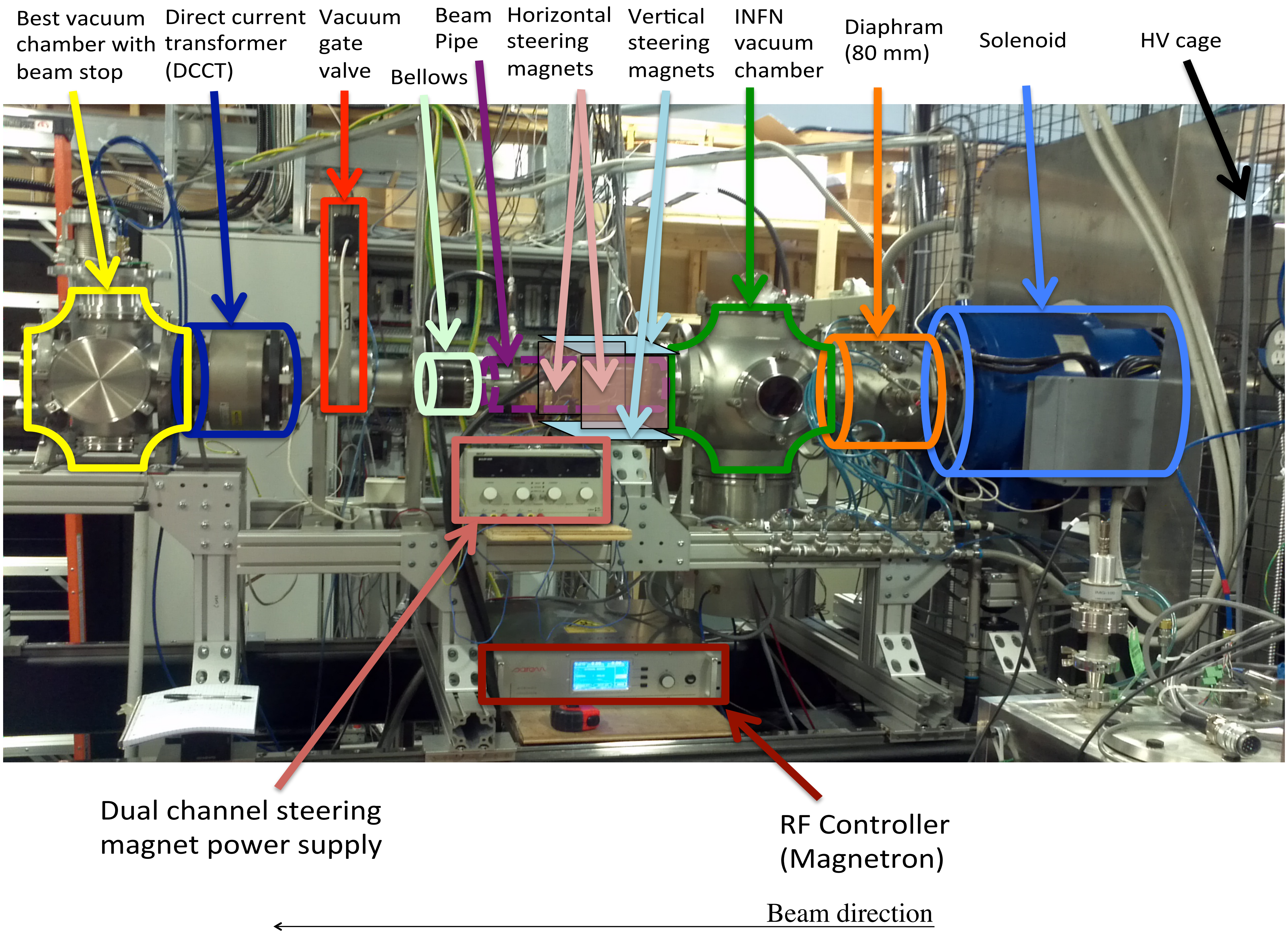
Beam has been characterized at Best Cyclotrons, Inc, Vancouver (Best Cyclotron Systems, INFN-Catania, and MIT -- NSF funded)



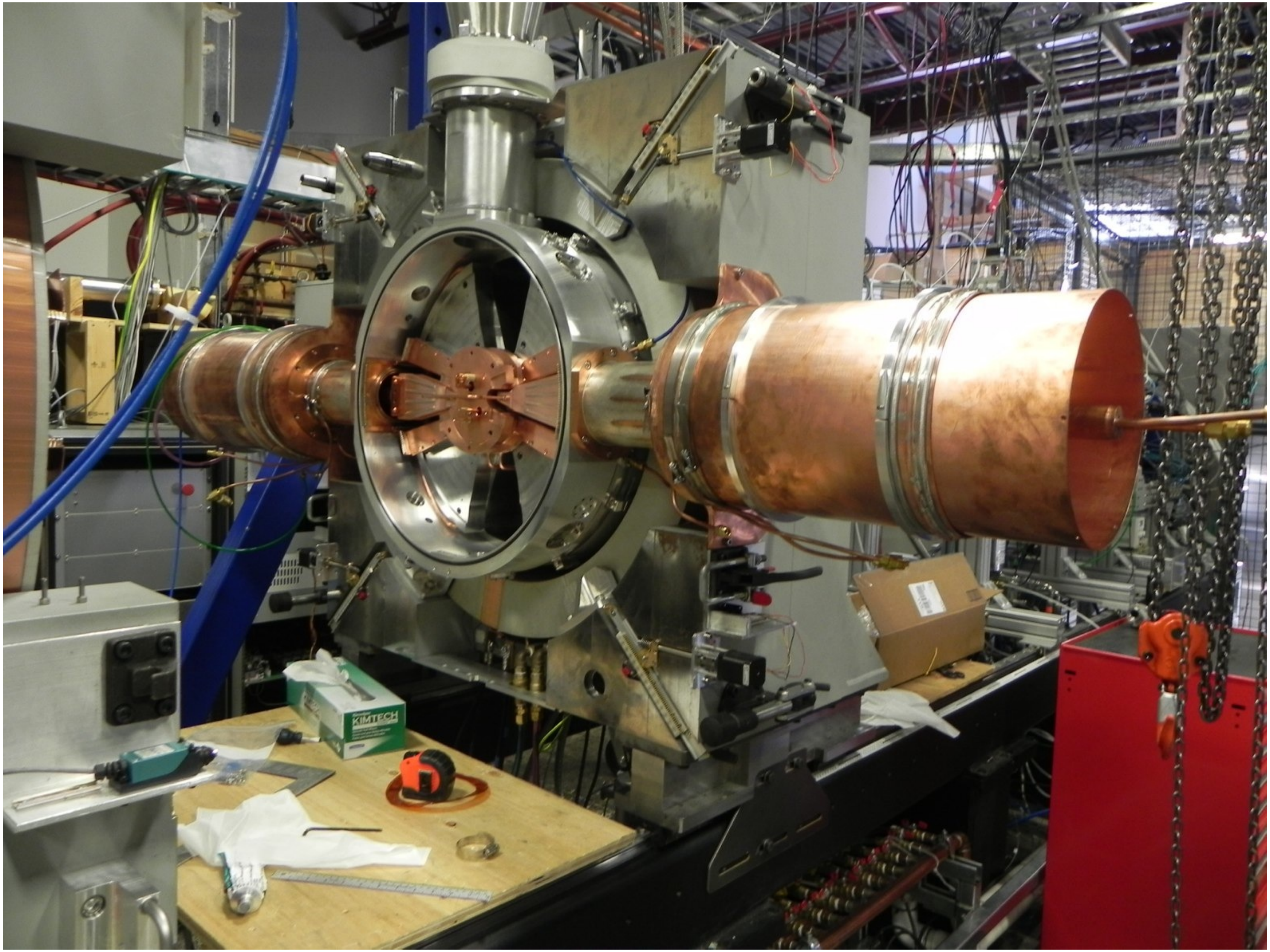


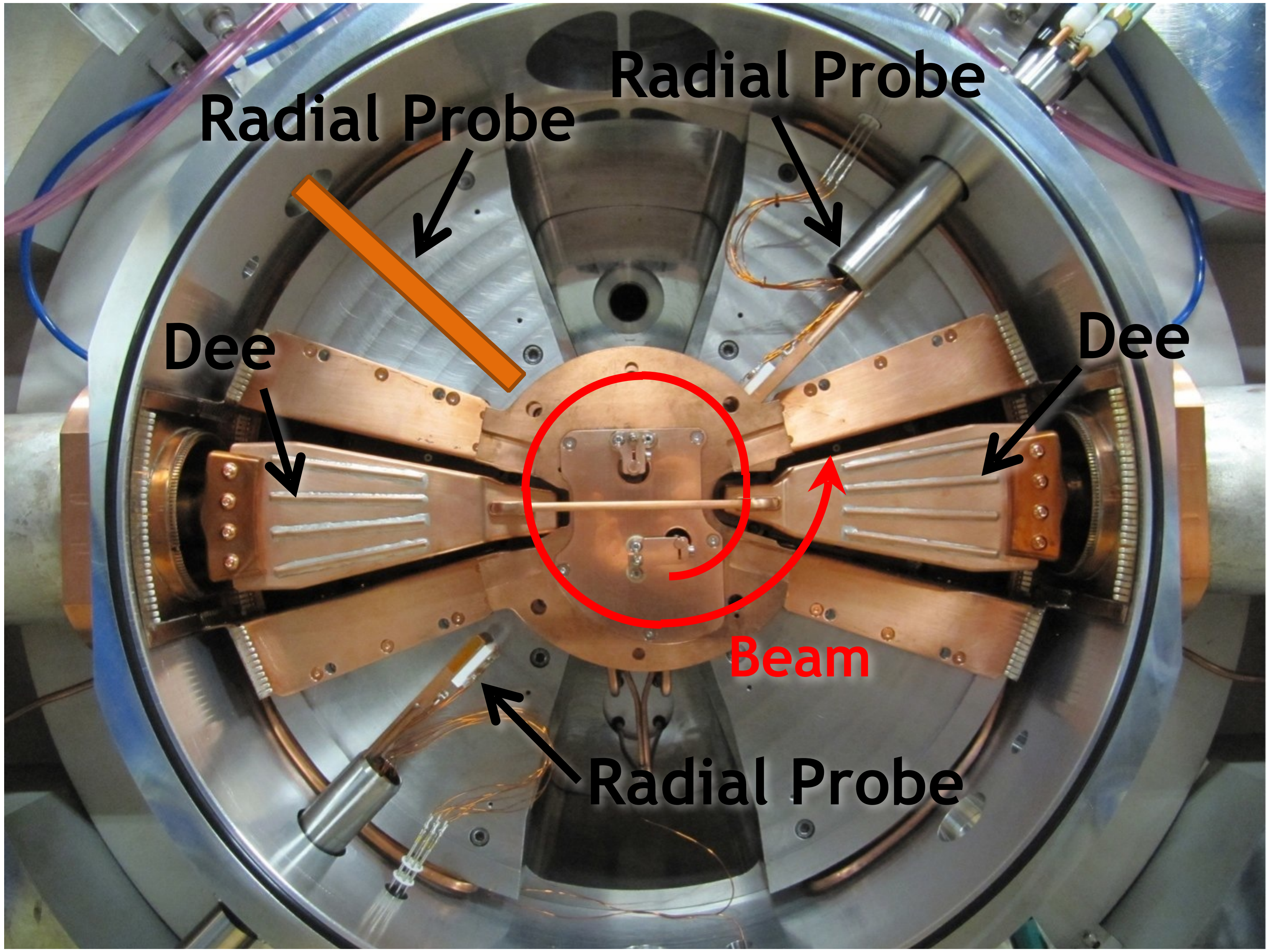


- Ion source from INFN-Catania installed at BEST Cyclotrons Inc. lab in Vancouver.
- 40 mA protons demonstrated (summer, 2013) and now focusing on H_2^+.
- Initial output is 12 mA (20-30 mA anticipated with new plasma chambers).


Best vacuum chamber with beam stop
Direct current transformer (DCCT)
Vacuum gate valve
Bellows
Beam Pipe
Horizontal steering magnets
Vertical steering magnets
INFN vacuum chamber
Diaphram (80 mm)
Solenoid
HV cage
Dual channel steering magnet power supply
RF Controller (Magnetron)
Beam direction

A cyclotron sits at the end of the line

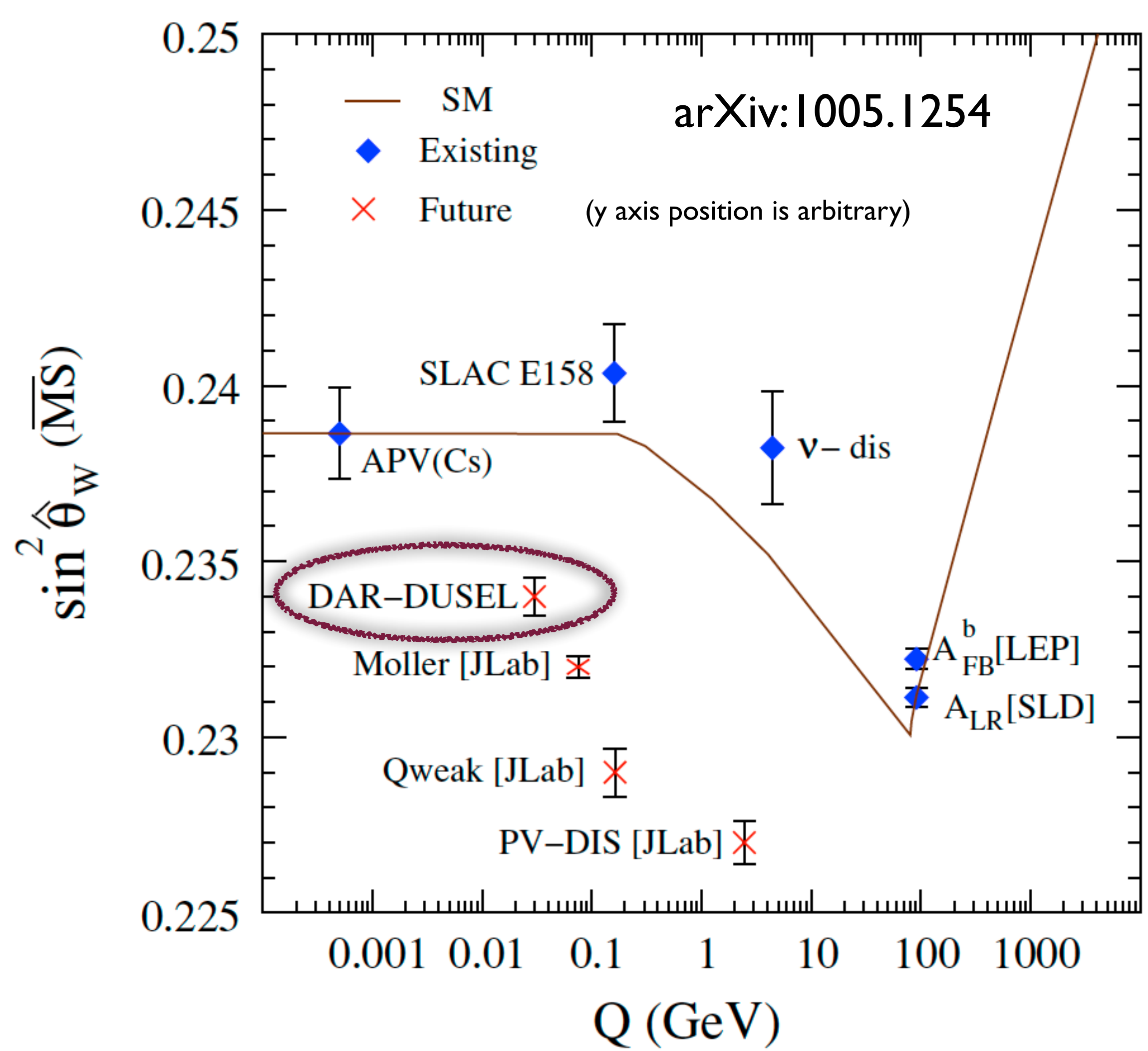




Beam has been brought from the ion source, through the low energy beam transport, through the axial inflector, and into the cyclotron where it is accelerated and makes several turns!

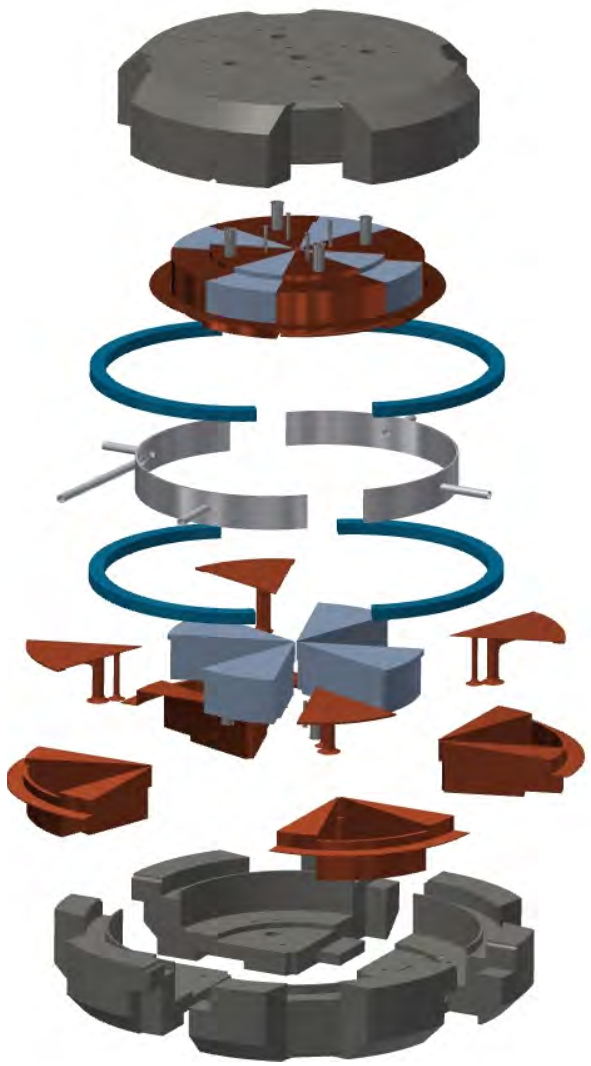
DAEδALUS and the weak mixing angle

- An intense decay-at-rest source, combined with an ultra-large detector, can provide a measurement of the weak mixing angle via neutrino-electron elastic scattering.
- ~20 million signal events yields 0.24% precision on $\sin^2\theta_W$ at Q~0.03 GeV.
    - [Assumes 100 kt water detector w/ 5 years and 8E22 nu/flavor/year]



JHEP 1108 059 (2011)

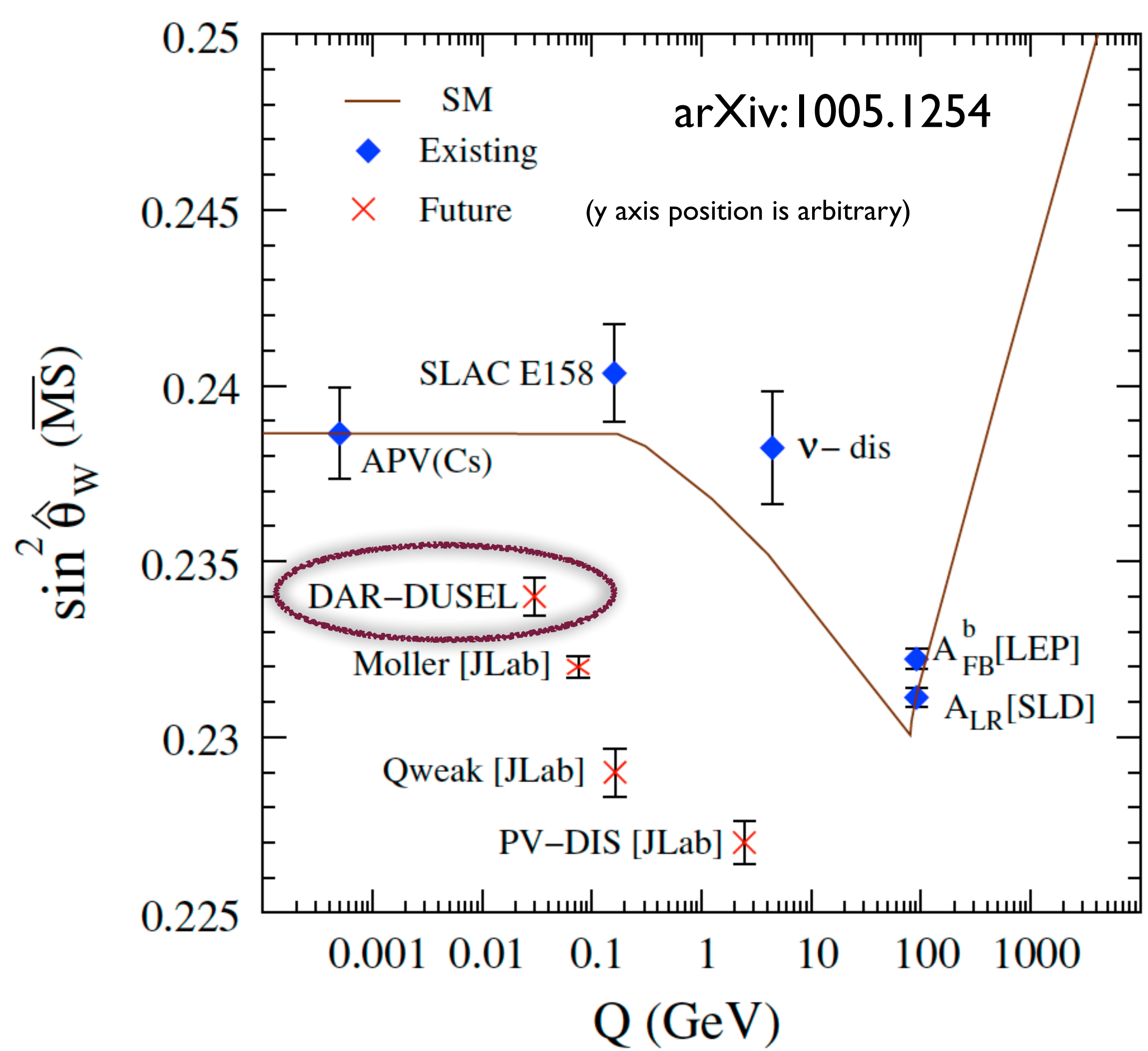
What is the IsoDAR timeline?



- Technically-driven schedule
- Currently proposed with KamLAND…but we have no schedule with KamLAND yet.
- First data in 2019, if we had funding now.

DAEδALUS and the weak mixing angle

- An intense decay-at-rest source, combined with an ultra-large detector, can provide a measurement of the weak mixing angle via neutrino-electron elastic scattering.
- ~20 million signal events yields 0.24% precision on $\sin^2\theta_W$ at Q~0.03 GeV.
  - [Assumes 100 kt water detector w/ 5 years and 8E22 nu/flavor/year]



JHEP 1108 059 (2011)

SN neutrinos

Channel	Observable(s)[a]	Interactions[b]
$\nu_x + e^- \to \nu_x + e^-$	C	17/10
$\bar{\nu}_e + p \to e^+ + n$	C, N, A	278/165
$\nu_x + p \to \nu_x + p$	C	682/351
$\nu_e + {}^{12}\mathrm{C} \to e^- + {}^{12}\mathrm{N}^{(*)}$	C, N, G	3/9
$\bar{\nu}_e + {}^{12}\mathrm{C} \to e^+ + {}^{12}\mathrm{B}^{(*)}$	C, N, G, A	6/8
$\nu_x + {}^{12}\mathrm{C} \to \nu_x + {}^{12}\mathrm{C}^*$	G, N	68/25
$\nu_e + {}^{16}\mathrm{O} \to e^- + {}^{16}\mathrm{F}^{(*)}$	C, N, G	1/4
$\bar{\nu}_e + {}^{16}\mathrm{O} \to e^+ + {}^{16}\mathrm{N}^{(*)}$	C, N, G	7/5
$\nu_x + {}^{16}\mathrm{O} \to \nu_x + {}^{16}\mathrm{O}^*$	G, N	50/12
$\nu_e + {}^{40}\mathrm{Ar} \to e^- + {}^{40}\mathrm{K}^*$	C, G	67/83
$\bar{\nu}_e + {}^{40}\mathrm{Ar} \to e^+ + {}^{40}\mathrm{Cl}^*$	C, A, G	5/4
$\nu_e + {}^{208}\mathrm{Pb} \to e^- + {}^{208}\mathrm{Bi}^*$	N	144/228
$\nu_x + {}^{208}\mathrm{Pb} \to \nu_x + {}^{208}\mathrm{Pb}^*$	N	150/55
$\nu_x + A \to \nu_x + A$	C	9,408/4,974

[a]The observables column lists primary observable products relevant for interactions in current detectors. Abbreviations: C, energy loss of a charged particle; N, produced neutrons; G, deexcitation γs; A, positron annihilation γs. Note there may, in principle, be other signatures for future detector technologies or detector upgrades.
[b]The interactions column gives interactions per kilotonne at 10 kpc for two different neutrino flux models for neutrino energies greater than 5 MeV, computed according to **http://www.phy.duke.edu/~schol/snowglobes**. No detector response is taken into account here, and actual detected events may be significantly fewer. For elastic scattering and inverse β decay, the numbers per kilotonne refer to water; for other detector materials, the numbers need to be scaled by the relative fraction of electrons or protons, respectively. For neutrino-proton elastic scattering, the numbers per kilotonne refer to scintillators.

Kate Scholberg

Annu. Rev. Nucl. Part. Sci. 2012. 62:81–103

SN neutrinos

Detector	Type	Mass (kt)	Location	Events	Live period
Baksan	C_nH_{2n}	0.33	Caucasus	50	1980–present
LVD	C_nH_{2n}	1	Italy	300	1992–present
Super-Kamiokande	H_2O	32	Japan	7,000	1996–present
KamLAND	C_nH_{2n}	1	Japan	300	2002–present
MiniBooNE[b]	C_nH_{2n}	0.7	USA	200	2002–present
Borexino	C_nH_{2n}	0.3	Italy	100	2007–present
IceCube	Long string	0.6/PMT	South Pole	N/A	2007–present
Icarus	Ar	0.6	Italy	60	Near future
HALO	Pb	0.08	Canada	30	Near future
SNO+	C_nH_{2n}	0.8	Canada	300	Near future
MicroBooNE[b]	Ar	0.17	USA	17	Near future
NOνA[b]	C_nH_{2n}	15	USA	4,000	Near future
LBNE liquid argon	Ar	34	USA	3,000	Future
LBNE with water Cherenkov	H_2O	200	USA	44,000	Proposed
MEMPHYS	H_2O	440	Europe	88,000	Future
Hyper-Kamiokande	H_2O	540	Japan	110,000	Future
LENA	C_nH_{2n}	50	Europe	15,000	Future
GLACIER	Ar	100	Europe	9,000	Future

[a]Neutrino event estimates are approximate for 10 kpc; note that there is significant variation by model. Not included are smaller detectors (e.g., reactor neutrino scintillator experiments) and detectors sensitive primarily to coherent elastic neutrino-nucleus scattering (e.g., weakly interactive massive particle dark matter search detectors).
[b]These entries are surface or near-surface detectors and will have larger backgrounds. Abbreviations: N/A, not applicable; PMT, photomultiplier tube.

Kate Scholberg

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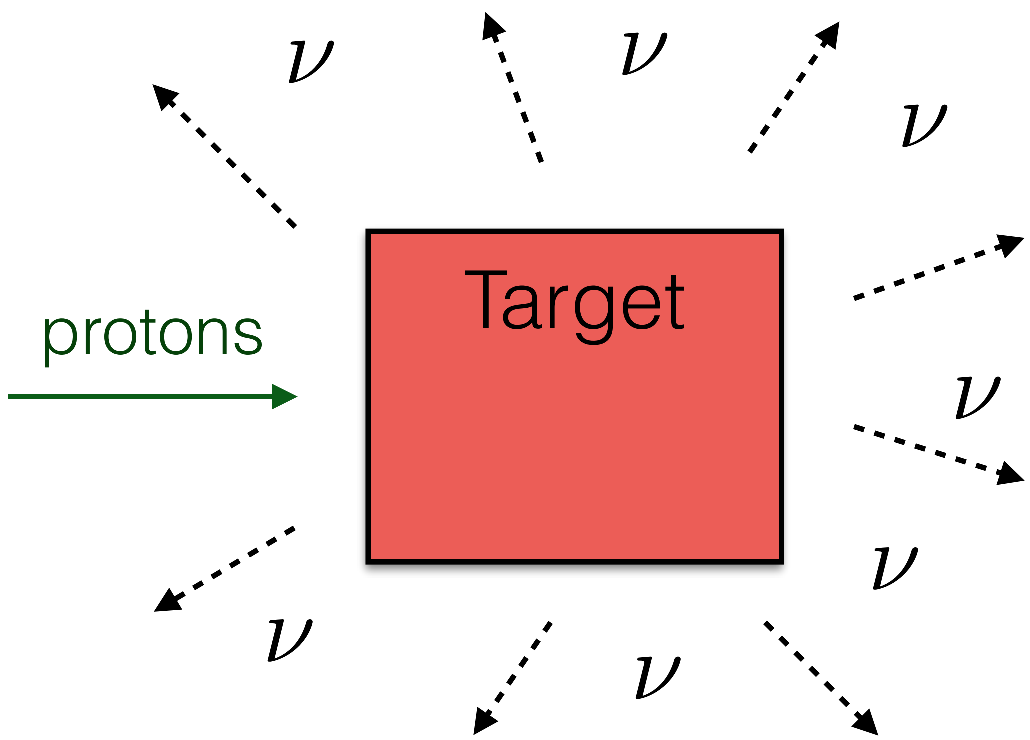
A sterile neutrino search w/ kaon decay at rest

Phys. Rev. D 85 093020 (2012)



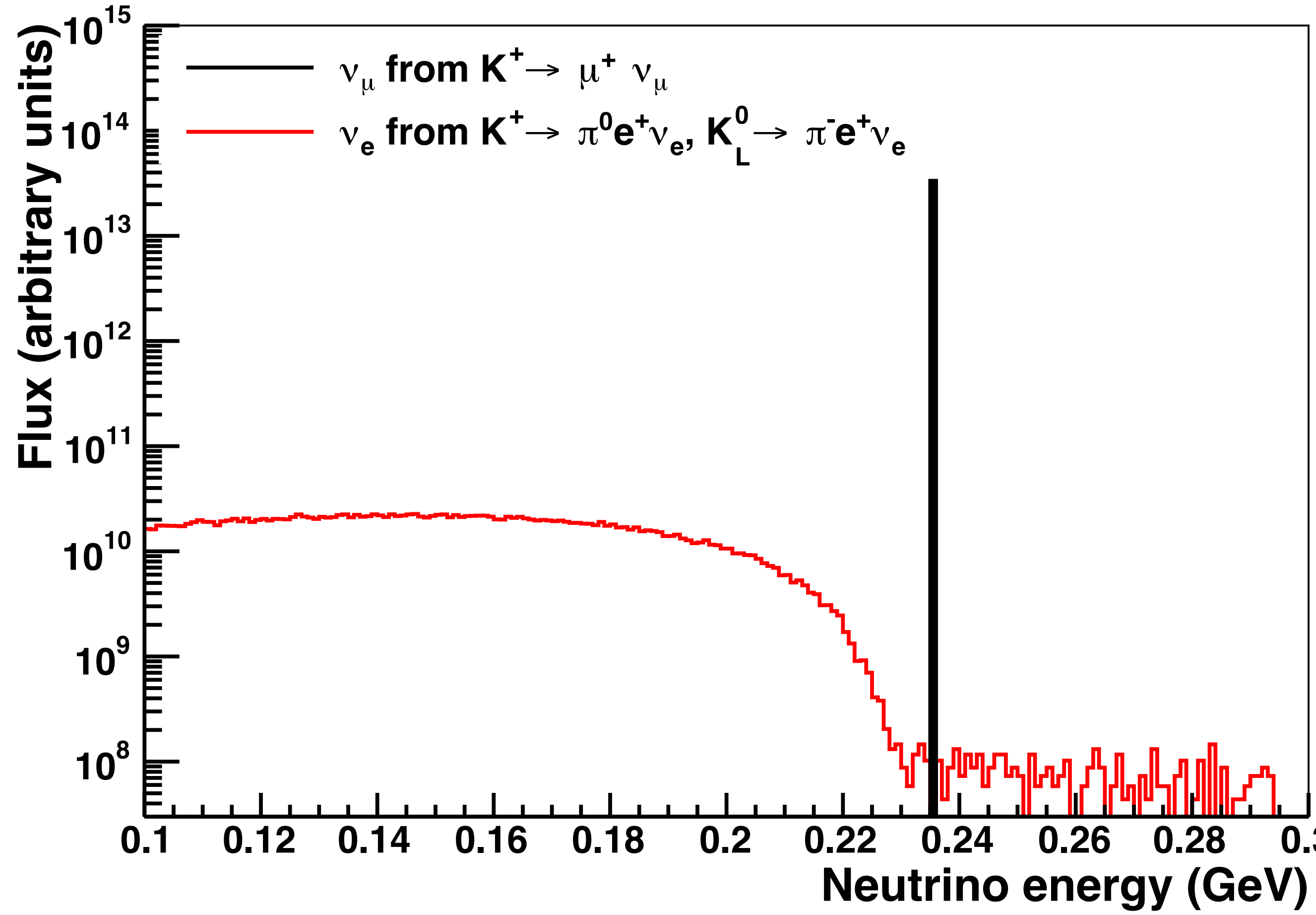
$$K^+ \to \mu^+ \nu_\mu$$

$$K^+ \to \pi^0 e^+ \nu_e$$

$$K_L^0 \to \pi^- e^+ \nu_e$$

$$\nu_\mu \to \nu_e \quad ?$$

Neutrino flux



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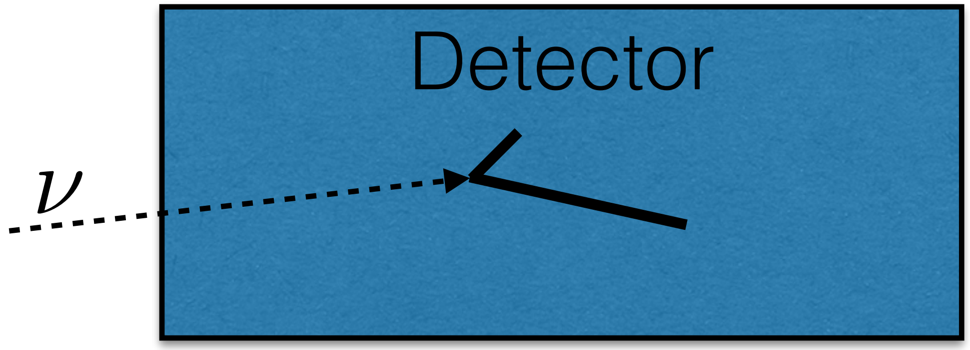
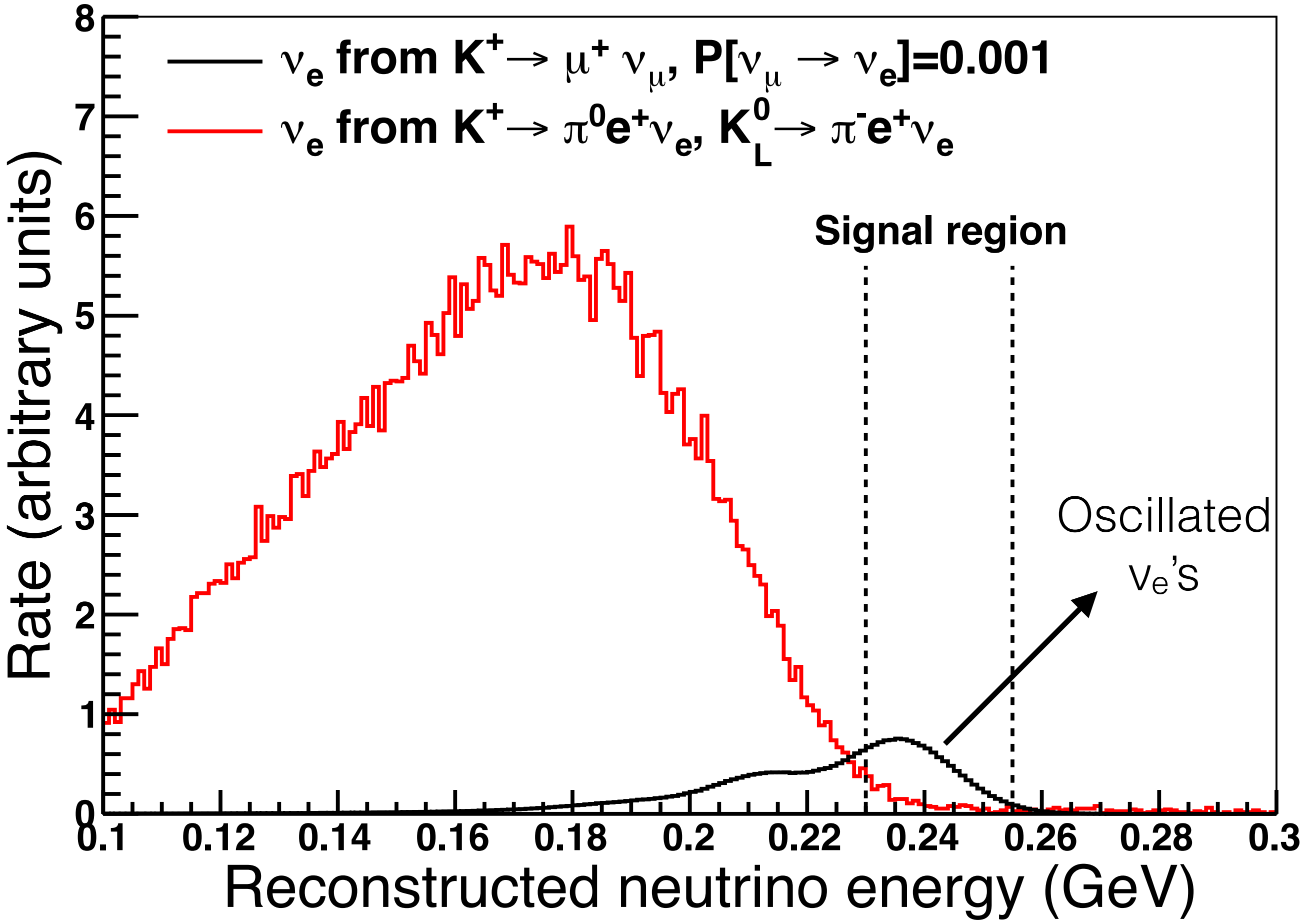


$$\nu_\mu \rightarrow \nu_e \quad ?$$

$$\nu_e n \rightarrow e^- p$$

Neutrino rate



- Look for an excess near the endpoint of a well understood and measured background distribution.